COMPACT HEAT EXCHANGERS
A TRAINING PACKAGE FOR ENGINEERS

PRODUCED BY THE

BEST PRACTICE PROGRAMME

ENERGY EFFICIENCY

COMPACT HEAT EXCHANGERS – GUIDANCE FOR ENGINEERS

This Package is issued by the Energy Efficiency Best Practice Programme and aims to increase the penetration of compact heat exchangers into industry by promoting awareness of the technology amongst graduate engineers in particular.

This modular Package is intended to provide University lecturers or other training forums such as Continuing Professional Development, with text, graphics, photographs and examples that can be easily incorporated into lecture material, course notes or similar. The full text and graphics are provided on the CD-ROM included with this Package.

All the text, graphics and photographs can be downloaded from the CD-ROM in WORD format. This material can be incorporated into lecture notes, presentations or similar without restriction for educational purposes. The source of commercial graphics materials should be acknowledged where appropriate.

This Training Package updates and combines information from the Good Practice Guides 89 and 198 already available through the Best Practice Programme. It provides information on compact heat exchanger technology, applications, selection, operation and Best Practice. To illustrate the potential benefits of compact heat exchanger designs, worked design examples are given comparing some compact exchanger designs with other more conventional exchangers.

The Training Package comprises six modules:

- Module 0 introduces the Package structure and contents.
- Module 1 describes the Package background and introduces compact heat exchangers in general.
- Module 2 provides details on individual compact heat exchanger technologies.
- Module 3 addresses aspects and issues common to all heat exchangers.
- Module 4 presents initial design selection examples.
- Module 5 gives other information.

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and

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Contact information for the organisations above are given in Modules 5.2 and 5.3.

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Other relevant titles in the Good Practice Guide Series

89. GUIDE TO COMPACT HEAT EXCHANGERS
141. WASTE HEAT RECOVERY IN THE PROCESS INDUSTRIES
168. CUTTING YOUR ENERGY COSTS
198. EXPERIENCE IN THE OPERATION OF COMPACT HEAT EXCHANGERS
244. PROCESS INTEGRATION

Copies of these guides may be obtained from:

Environment and Energy Helpline
Telephone: 0800 585794
Fax: 01235 433066

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ABBREVIATIONS

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q}/\Delta T$	£/(W/K)
C*	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
D	diameter	m
F_θ	temperature function	
F_T	logarithmic temperature difference correction factor	
GPG	Good Practice Guide	-
h	specific enthalpy	J/kg
LMTD	Log Mean Temperature Difference	K
$\dot{M}$	mass flow-rate	kg/s
N	number	-
Nu	Nusselt number	-
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
Pr	Prandtl number	
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R	flow heat capacity ratio	-
Re	Reynolds number	-
R_f	fouling resistance	m^2.K/kW
R_K	$(\dot{M}Cp)_h/(\dot{M}Cp)_c$	-
T	stream temperature	K
ΔT	temperature difference	K
u	flow velocity	m/s
U	overall heat transfer coefficient	W/m^2K
$<$	less than	-
$>$	up to	-
α	film coefficient	-
λ	thermal conductivity	
μ	viscosity	
ρ	density	kg/m^3

Units

K	Kelvin	m^2	square metre	mm	millimetre
kg	kilograms	m^3	cubic metre	PJ	petajoule
kW	kilowatts	m	metre	W	watts

Subscripts

av	average	fg	phase change	m	mean
c	cold	h	hot	out	out
calc	calculated	H	hydraulic	overall	overall
ch	channel	i	isothermal	p	pressure
clean	clean	in	in	plate	plate
f	fouled	larger	larger	smaller	smaller

GUIDE TO THE COMPACT HEAT EXCHANGER TRAINING PACKAGE

MODULE 0.0

GENERAL INFORMATION

This module presents the Package structure and gives instructions for use.

Contents

0.0.1 General Information
0.0.2 Package Structure

0.0.3 User Instructions
0.0.3.1 Accessing the Package Material
0.0.3.2 Downloading Information

0.0.4 System Requirements

List of Figures

0.0.1 Size Comparison Between Printed Circuit and Shell and Tube Designs of Equal Duty
0.0.2 Package Modular Structure
0.0.3 Brazed Plates

GENERAL INFORMATION

0.0.1 General Information

This Package summarises and updates material published by the Energy Efficiency Best Practice Programme on the industrial experience of compact heat exchanger designs and operation. It seeks to increase the awareness of trainee engineers of the technology available, its likely applications and criteria to be used when making equipment selections.

Although the Package is aimed at an academic forum, it is relevant to engineers, designers and equipment specifiers in the following industrial sectors:

- Chemicals and petrochemicals.
- Cryogenics.
- Food and drink.
- Paper and board.
- Textiles and fabric care.
- Oil and gas processing.
- Prime movers.
- Energy.

The Government has been supporting the development of compact heat exchangers and promoting their use, particularly in the process industries, for more than eight years.

As well as R&D activities and the promotion of Case Studies, the programme has resulted in:

- Publication of Good Practice Guide 89, Guide to Compact Heat Exchangers.
- Production of CHEX, a computer software package designed to assist the compact heat exchanger selection process (part of Good Practice Guide 89).
- Publication of Good Practice Guide 198, Experience in the Operation of Compact Heat Exchangers.

In appropriate applications, compact heat exchangers offer a number of advantages over more conventional designs including:

- Improved heat exchanger effectiveness, closer approach temperatures and high thermal effectiveness.
- Smaller volume and weight for a given duty.
- Lower installed cost (in most cases).
- Multi-stream and multi-pass configurations.
- Tighter temperature control.
- Energy savings.
- Reduced inventory volume giving short residence times.
- Process intensification by using reactor exchangers.

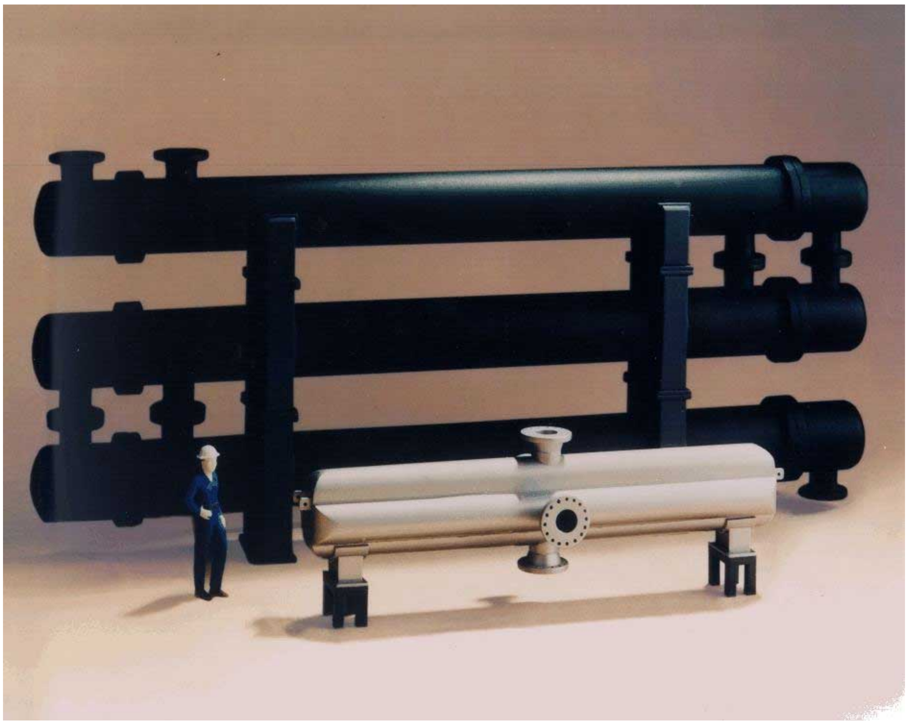


Figure 0.0.1 – Size Comparison Between Printed Circuit and Shell and Tube Designs of Equal Duty (Courtesy of Heatric Ltd)

0.0.2 Package Structure

This Package is intended to enable quick reference to text, graphics and picture information associated with compact heat exchangers. Therefore, the information is provided on the Energy efficiency website and as a self-loading, menu-driven CD-ROM. The CD-ROM information includes the full Training Package in WORD format, an Adobe Acrobat pdf file and the graphics files linked to the WORD file. The website presents the Adobe Acrobat pdf file only.

> The information given in this Package is intended for augmenting or updating course-notes and lecture material used for educational purposes.
>
> Lecturers are invited to incorporate any information from this Package directly into lecture material, course notes or other educational aids.

Figure 0.0.2 summarises the Training Package structure. The Contents Page provides further details.

Instructions for using the accompanying CD-ROM are given in Section 0.0.3.

All modules are presented in a common format.

Title Page

0.0 General Information

Interactive Contents Page

1.0 Introduction to Compact Heat Exchangers

2.0 Heat Exchanger Technology Modules

2.1 Plate Exchanger Types
2.2 Plate-fin Exchangers
2.3 Spiral Exchangers
2.4 Printed Circuit Exchangers
2.5 Graphite Block Exchangers
2.6 Polymer Exchangers
2.7 Plate and Shell Exchangers

3.0 Common Aspect Modules

3.1 Advantages and Limitations
3.2 Fouling
3.3 Applications
3.4 Energy Efficiency
3.5 Heat Transfer Enhancement
3.6 Specification and Selection
3.7 Process Intensification
3.8 Software

4.0 Examples

4.1 Selection of a welded plate exchanger
4.2 Selection of a gasketed plate exchanger
4.3 Selection of a plate-fin exchanger
4.4 Selection of a printed circuit exchanger
4.5 Selection of a shell and tube exchanger

5.0 Other Information

5.1 References
5.2 Further Reading
5.3 Technology Suppliers
5.4 Energy Efficiency Best Practice Programme

Figure 0.0.2 – Package Modular Structure

0.0.3 User Instructions

The compact disk provides you with unrestricted access to the Compact Heat Exchangers Training Package. Either the Training Package can be viewed and printed as a fully indexed pdf in Adobe Acrobat, or loaded as a WORD file for full manipulation. Alternatively, graphics files may be downloaded directly.

> The Training Package provides reference material intended for augmenting and updating course-notes or lecture-aids used for educational purposes. Lecturers and trainers are invited to incorporate text, equations, photographs, graphics or other information directly into lecture material, course notes or other educational aids. Users are requested to acknowledge the source of graphic material where appropriate.

CD Structure

D: Training Package
- \Training Package (WORD97 file)
- \graphics (jpeg image files)
- \Training Package (Acrobat pdf file)

0.0.3.1 Accessing the Package Material

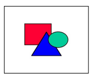
1. Load the CD and follow the on-screen instructions to select the file format required.

   Select the WORD format for viewing, printing, copying and saving.
   Select the Adobe Acrobat pdf format for viewing and printing.

2. If the WORD option is selected, WORD is automatically loaded and the Training Package is presented with full user access.

   The WORD file graphics are linked to the D:\graphics directory. For the graphic files to load, the CD must be in the D: drive. If the Training Package is independently saved, the graphics will remain linked to CD.

   To transfer graphics to other files, select the image required in the Training Package, copy, paste into new file, then select picture and break link to CD (Main menu; Edit; Links; Break Links).

   When the programme is seeking an image linked to the CD, then  will appear at image sites if the CD is not available.

   Alternatively, individual graphics can be directly accessed from the CD using jpeg image viewer software, such as photograph editors or Internet browsers.

   To navigate throughout the Training Package, use the Contents Page or the WORD search facility (Edit, Find).

3. If the Adobe Acrobat option is selected, Adobe Acrobat is automatically loaded and the Training Package is presented with an interactive contents page.

   The pdf file can be viewed and printed in the Adobe Acrobat environment.

4. To move between windows use ALT+TAB.

5. To exit the CD programme, move to the CD window and then press the EXIT button

0.0.3.2 Downloading Information

Material can be fully manipulated in the WORD environment. If required, the graphic jpeg format images can be directly accessed on the CD using appropriate software, or can be directly inserted into other software packages.

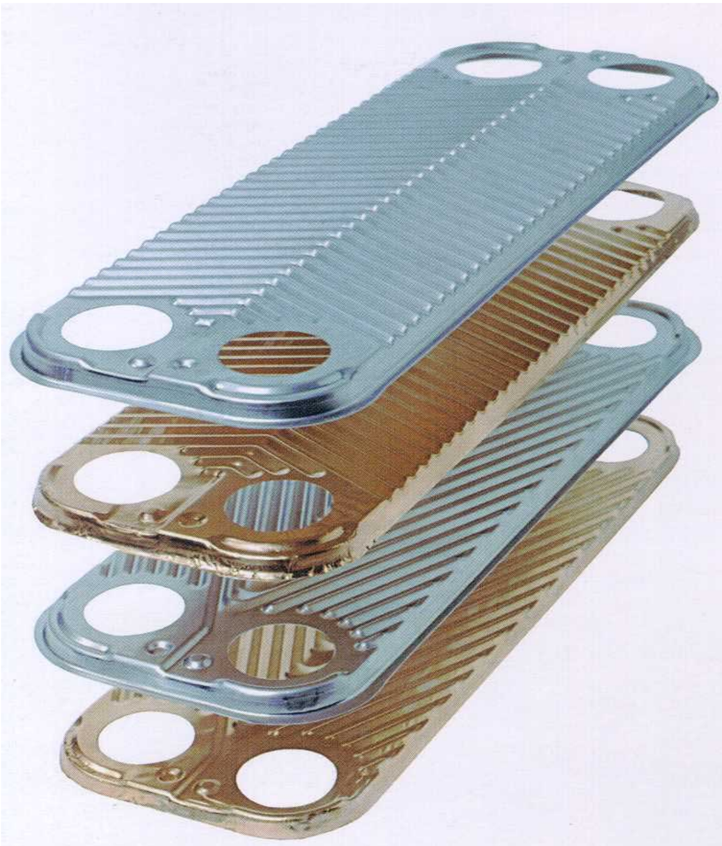


Figure 0.0.3 – Brazed Plates
(Courtesy of Alfa Laval Thermal Division)

0.0.4 System Requirements

Minimum Computer System Requirements

Computer Specification	Software Specification
Pentium 90 processor	Windows 95 or NT
Hard disk drive	Microsoft WORD 97
4 x speed CD drive (designated as the D: drive)	Adobe Acrobat Reader 3
256 + Colour Monitor	(or above)
32 Mb RAM recommended	
Mouse	

GUIDE TO COMPACT HEAT EXCHANGER TRAINING PACKAGE

MODULE 1.0

INTRODUCTION TO COMPACT HEAT EXCHANGERS

This module describes the Package background and introduces compact heat exchangers in general.

Contents

1.0.1 Background
1.0.2 Objectives
1.0.3 Generic Technology Definition
1.0.4 Compact Heat Exchanger Types

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1.0.2 Compact Heat Exchanger Duties
1.0.3 Comparative Summary of Compact Heat Exchanger Features

List of Figures

1.0.1 Picture of Plate and Frame Exchanger
1.0.2 Relative Size of Spiral and Shell and Tube Heat Exchangers

INTRODUCTION TO COMPACT HEAT EXCHANGERS

1.0.1 Background

Compact heat exchangers (CHEs) are not a new technology although innovative designs are continuously being produced to suit market requirements. Compact heat exchangers are characterised by high heat transfer surface-area to volume ratios (typically 200 to 300 m^2 per m^3, or more) and high heat transfer coefficients compared to other exchanger types. Such designs are more efficient in terms of heat transfer although fouling and pressure are important design considerations that make compact heat exchangers not suitable for all applications.

The Government has already recognised the importance of compact heat exchangers in energy efficiency terms and has published material via the Energy Efficiency Best Practice Programme (EEBPP). The primary publication is Good Practice Guide 89 (GPG 89; 1994 with revisions) and its associated software programme. GPG 198, 1998 addresses the implications of operating compact heat exchangers.

A survey of process engineers conducted by Newcastle University indicated that there are still a number of perceived problems in the use of compact heat exchangers. The most significant of these are fouling, lack of awareness, conservatism and concern about standards. A subsequent Steering Group comprising academic lecturers, equipment users and equipment suppliers confirmed this finding and suggested how the information could be provided to address these issues.

A selected group of academic and industry experts believe that there is a deficiency in the way Universities are teaching undergraduates about the benefits of compact heat exchanger designs. This is reversible through the provision of more information and examples in a format suitable for incorporation into lecture materials.

This Package has arisen from the observation that compact heat exchanger designs are only a small component of university course information prepared for undergraduates, but this component could be increased if more suitable source material was easily available.

Today's graduate engineers are generally unaware that compact heat exchanger designs can save energy and may cost less to buy and operate.

1.0.2 Objectives

This Training Package is concerned with compact heat exchangers and their application in the UK process industries. Its specific aims are to provide information on:

- The types and characteristics of compact heat exchangers commercially available.
- The potential benefits of using compact heat exchangers.
- The common applications of compact heat exchangers.
- The factors to be taken into account when designing, selecting and operating compact heat exchangers

The potential market for compact heat exchangers in the UK has grown significantly, helped by the continuing development of new types. The use of compact heat exchangers can offer a number of benefits over conventional designs, as discussed in Module 3.1.

The technology could provide significant energy benefits: a national energy saving potential of **8** PJ/year, worth **£20** million annually, has been estimated. Compact heat exchangers are, however, just one area of heat exchanger development. Developments in shell and tube heat exchangers, enhanced heat transfer, etc all have an important role to play in the advancement of heat exchanger technology.

One of the major barriers to the increased use of compact heat exchangers has been the lack of information on industrial installations across a range of applications. Such information is particularly important to smaller companies that do not have the resources to keep abreast of developing technologies.

Although compact heat exchangers are not suitable for all heat exchange duties in the UK their potential has been significantly under-exploited by many industrial sectors. Through the University courses, graduate engineers are urged to take a 'fresh look' at some of the current and emerging technologies in heat transfer.

This training package, as complemented by the range of other Energy Efficiency Best Practice Programme Good Practice Guides, New and Good Practice Case Studies, is intended to increase awareness of compact heat exchangers in universities, smaller companies and to provide advisory information on the technology for larger companies.

The Package covers the known range of compact heat exchangers currently available or under development in the UK in 1999.

Figure 1.0.1 – Plate Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

1.0.3 Generic Technology Definition

Compact heat exchangers are characterised by their high 'area density': this means that they have a high ratio of heat transfer surface to heat exchanger volume. Because of this, the initial development and use of compact heat exchangers was in the aerospace, road transport and marine sectors.

One somewhat arbitrary definition of a compact heat exchanger is having an area density (area/volume ratio) greater than 500 m^2/m^3. However, this strictly refers to the gas side of a gas-liquid heat exchanger. Table 1.0.1 lists the threshold area/volume densities of a range of generic heat exchanger types that could all be classed as 'compact'.

Compact Heat Exchanger Type	Area Density (m^2/m^3)[(1)]
Liquid-liquid	$\geq$200
Gas-liquid	$\geq$500
Gas-Gas	$\geq$500

Notes:
(1) The area density includes secondary surfaces, such as fins.

Table 1.0.1 - Area Densities of Generic Compact Heat Exchanger Types

A conventional shell and tube heat exchanger with 19 mm diameter tubes has an area density of about 100 m^2/m^3 on one fluid side although there are some 'compact' shell and tube heat exchangers with higher heat transfer areas.

Other types of heat exchanger also may be regarded as 'compact', for example the rotating regenerator or heat wheel type frequently has an area ratio in excess of 5,000 m^2/m^3. However, these are outside the scope of this Package.

Compact heat exchangers are commonly used for both single phase and two-phase applications as shown in Table 1.0.2.

Type	Nature of Streams
Gasketed plate and frame	Liquids; two-phase [(1)]
Brazed plate	Liquids; two-phase
Welded plate and frame	Liquids; two-phase [(2)]
Plate-fin	Gases; liquids; two-phase
Printed circuit	Gases; liquids; two-phase
Welded stacked plate	Gases; liquids; two-phase
Compact shell and tube	Liquids; two-phase

Notes:
(1) Two-phase includes boiling and condensation.
(2) One flow path may have welded plates, the other retaining gaskets.

Table 1.0.2 - Compact Heat Exchanger Duties

1.0.4 Compact Heat Exchanger Types

There are various types of compact heat exchanger currently easily available from technology suppliers.

These include:

- Plate Heat Exchanger Types (Technology Module 2.1)
  - Plate and Frame Heat Exchangers
  - Partially Welded Plate Heat Exchangers
  - Brazed Plate Heat Exchangers
  - The Bavex Hybrid Welded Plate Heat Exchanger
  - The Platular Welded Plate Heat Exchanger
  - The Compabloc Welded Plate Heat Exchanger
  - The Packinox Welded Plate Heat Exchanger
  - The Alfa-Rex Welded Plate Exchanger

- Plate-Fin Heat Exchangers (Technology Module 2.2)
  - Brazed Plate-Fin Heat Exchangers
  - Diffusion-Bonded Plate-Fin Heat Exchangers

- Spiral Heat Exchangers (Technology Module 2.3)

- Printed Circuit Heat Exchangers (Technology Module 2.4)

- Plate and Shell Heat Exchangers (Technology Module 2.5)

- Polymer Heat Exchangers (Technology Module 2.6)

Each generic exchanger technology is described in a separate module. In each module, there is a brief introductory description followed by information on construction, construction materials, operating limits and principal applications (see also Module 3.3 - Applications). Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise the size and weight reductions that can be achieved by using compact heat exchangers.

Common aspects and issues for all compact heat exchanger types are discussed in Module 3 – Common Aspects. This module presents information on advantages and limitations of compact designs, fouling, applications, enhancing technology and specifying equipment.

Specific design examples for some compact designs are given in Module 4 – Examples.

Module 5 includes references, further information sources, current technology suppliers and information on the Energy Efficiency Best Practice Programme funded by the Government.

Consideration is also given to heat exchangers handling a variety of gases, liquids and two-phase streams.

Shell and tube heat exchangers are often specified for applications potentially suitable for compact heat exchangers on the basis that "no engineer ever got dismissed for specifying a shell and tube exchanger". In fact, many graduate engineers leave university without more than a theoretical reference to compact types and their potential applications.

Although this Package is not intended as a design manual, the general issues associated with specifying designs are discussed. This includes a generic discussion of fouling, energy efficiency, advantages and limitations, and common applications. Information on process intensification and on some software programs commercially available is given together with other information linked to energy efficiency in general.

There is a multitude of different heat exchanger designs available commercially. Each is designed for unique applications operating under specified conditions. Detailed information on heat exchange technologies is mainly held by the equipment suppliers and by users with operational experience.

To illustrate the complexity of this area, a comparative summary of the principal features of common compact heat exchanger designs is given in Table 1.0.3.

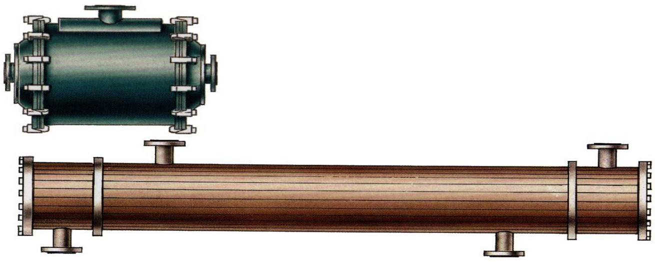

Figure 1.0.2 – Relative size of Spiral and Shell and Tube Heat Exchangers
(Courtesy of Alfa Laval Thermal Division)

Table 1.0.3 - Comparative Summary of Compact Heat Exchanger Features

Type of Heat Exchanger	Area Density (m^2/m^3) (0)	Stream Types (1)	Materials (3)	Temperature Range (^oC)	Maximum Pressure (bar) (2)	Fluid Limitations	Cleaning Methods	Corrosion Resistance (18)	Multi-stream Capability	Multi-pass Capability
Plate and frame (Gasketed)	→200	liquid-liquid gas-liquid two-phase	s/s, Ti, Incoloy Hastelloy, graphite, polymer	-25 to +175 Special –35 to +200	Normal 25 Special 40	Limited by gasket type. Not normal for gases	Mechanical (14) Chemical	Good (7)	Yes (9)	Yes
Partially welded plate	→200	gas-liquid liquid-liquid two-phase	s/s, Ti, Incoloy Hastelloy	-35 to +200	25	Few - Some types need clean fluids	Mechanical (4, 14) Chemical (6)	Good (7)	No	Yes
Fully welded plate (AlfaRex)	→200	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Ni alloys	-50 to +650	40	Few - Some types need clean fluid	Chemical	Excellent	No	Yes
Brazed plate	→200	liquid-liquid two-phase	s/s	Cu braze –195 to +220 Ni braze →400	Cu braze 30 Ni braze 16	Must be compatible with braze	Chemical (5)	Good (8)	No	No (10)
Bavex plate	200 - 300	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ni, Cu, Ti, Special steels	-200 to +900	60	Few	Mechanical (11, 9) Chemical	Good	In principle	Yes
Platular plate	200	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Hastelloy, Ni alloys	-180 to +700	40	Few	Mechanical (12, 14)	Good	Yes (13)	Yes
Compabloc plate	→300	liquid-liquid two-phase	s/s, Ti, Incoloy	→300	32	Few	Mechanical (14)	Good	Not usually	Yes
Packinox Plate	→300	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Hastelloy, Inconel	-200 to +700	300	Few	Mechanical (16, 14)	Good	Yes (9)	Yes
Spiral	→200	gas-liquid liquid-liquid two-phase	c/s, s/s, Ti, Incoloy, Hastelloy	→400 Special →850	30	Few	Mechanical (14)	Good	No	No

Type of Heat Exchanger	Area Density (m^2/m^3) (0)	Stream Types (1)	Materials (3)	Temperature Range (°C)	Maximum Pressure (bar) (2)	Fluid Limitations	Cleaning Methods	Corrosion Resistance (18)	Multi-stream Capability	Multi-pass Capability
Brazed plate-fin	800 – 1,500	gas-gas gas-liquid liquid-liquid two-phase	Al, s/s, Ti Ni alloy	Al –270 to +200 s/s cryogenic to +650	120	Low fouling Many limitations with Al	Chemical	Good	Yes	Yes
Diffusion-bonded plate-fin	700 - 800	gas-gas gas-liquid liquid-liquid two-phase	Ti, s/s, Ni	→400	200	Low fouling	Chemical	Excellent	Yes	Yes
Printed circuit	200 - 5,000	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ni, Ni alloys Ti	-200 to +900	500	Low fouling	Chemical	Excellent	Yes	Yes
Polymer - compact shell and tube	→275	liquid-liquid	Teflon	→200	11	Few	Water wash	Excellent	No	No
Plate and shell	→200	liquid-liquid	s/s, Ti, (shell also in c/s) (15)	-200 to +900	100	Few	Mechanical (16, 14) Chemical (17)	Good	No	Yes
Shell and tube (19)	→100	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, (shell also in c/s), many different materials	-100 to +600	Shell 300 Tubes 1400	Few	Mechanical (16, 14) Chemical (17)	Good	No	Yes

Notes for Table 1.0.3 → = up to, s/s = stainless steel, Ti = titanium, Ni = nickel, Al = aluminium, Cu = copper, c/s= carbon steel

(0) Area includes the secondary surface (such as fins)
(1) Two-phase includes boiling and condensing duties
(2) The maximum pressure capability is unlikely to occur at the higher operating temperatures, and assumes no pressure/stress-related corrosion
(3) Other special alloys are frequently available
(4) On gasket side
(5) Ensure compatibility with copper braze
(6) On welded side
(7) Function of gasket as well as plate material
(8) Function of braze as well as plate material
(9) Not common
(10) Not in a single unit
(11) On tube side
(12) Only when flanged access provided, otherwise chemical cleaning
(13) Five fluids maximum
(14) Can be dismantled
(15) Shell may be composed of polymeric material
(16) On shell side
(17) On plate or tube side
(18) Primarily a function of construction materials rather than the exchanger type
(19) Not a compact exchanger technology (given for comparison)

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.0

HEAT EXCHANGER TECHNOLOGY MODULES

This module series contains descriptions of the compact heat exchanger technologies, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

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2.1 Plate Exchanger Types
2.2 Plate-Fin Exchangers
2.3 Spiral Exchangers
2.4 Printed Circuit Exchangers
2.5 Plate and Shell Exchangers
2.6 Polymer Exchangers

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.1

PLATE HEAT EXCHANGER TYPES

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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PLATE HEAT EXCHANGER TYPES

2.1.1 Plate and Frame Heat Exchangers

2.1.1.1 Introduction

The plate and frame heat exchanger was one of the first compact exchangers to be used in the UK process industries, being originally introduced in 1923; the first plates were made of gunmetal. It is currently second to the shell and tube heat exchanger in terms of market share.

The most common variant of the plate and frame heat exchanger consists of a number of pressed, corrugated metal plates compressed together into a frame. These plates are provided with gaskets, partly to seal the spaces between adjacent plates and partly to distribute the media between the flow channels. The most common plate material is stainless steel.

Plate and frame heat exchangers were first used in the food and dairy industries, where the ability to access plate surfaces for cleaning is imperative.

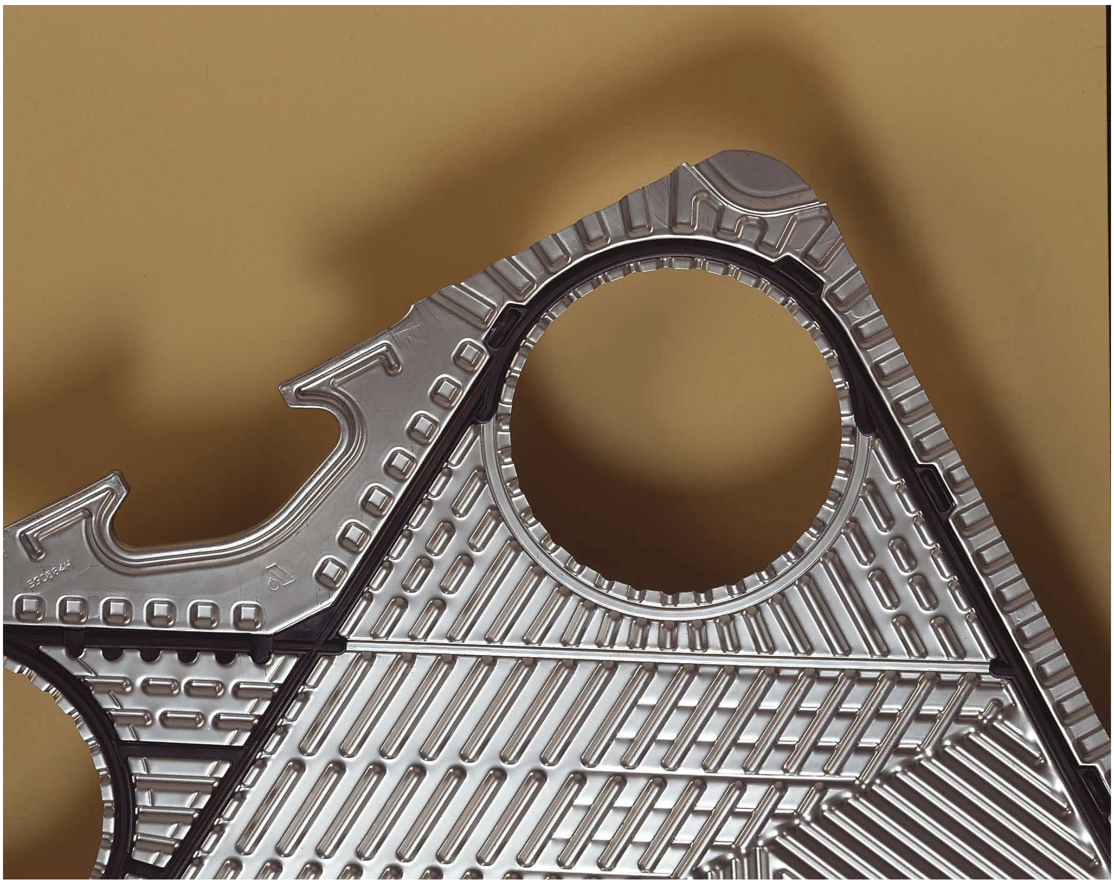

Figure 2.1.1 – Close-up View of a Heat Exchanger Plate
(Courtesy of APV)

There are numerous suppliers of plate and frame heat exchangers. While all manufacturers follow the same basic construction method, the differences in performance claimed tend to be associated with the patterns on the plates that form the flow channels, and the choice of gasket materials. Newer designs can accommodate features such as grossly unequal flow rates on each side of the plate.

2.1.1.2 Construction

Figure 2.1.2 shows an exploded view of a typical plate and frame heat exchanger design.

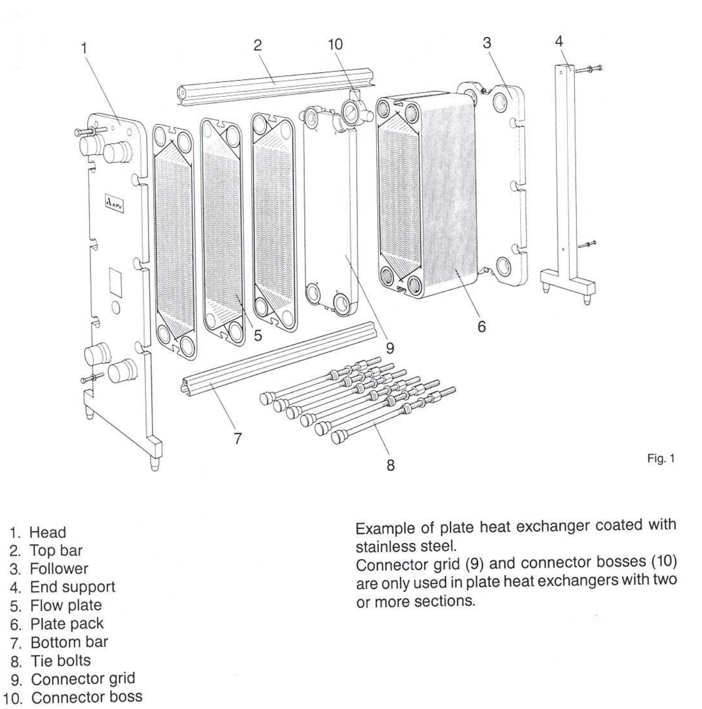

Figure 2.1.2 - Exploded View of a 'Food Style' Plate and Frame Heat Exchanger (Courtesy of APV)

The heat transfer surface consists of a number of thin corrugated plates pressed out of a high grade metal. The pressed pattern on each plate surface induces turbulence and minimises stagnant areas and fouling. Unlike shell and tube heat exchangers, which can be custom-built to meet almost any capacity and operating conditions, the plates for plate and frame heat exchangers are mass-produced using expensive dies and presses. Therefore, all plate and frame heat exchangers are made with what may appear to be a limited range of plate designs.

Although the plate heat exchangers are made from standard parts, each one is custom designed. Variation in the trough angle, flow path or flow gap can alter the N_{TU} of the heat exchanger. The N_{TU}, number of thermal units, is a dimensionless parameter equal to $UA / \dot{M}Cp$. When the trough angle is 90^o, the troughs run vertically. The flow passage made of such plates would resemble a collection of vertical tubes with low N_{TU} characteristics.

As the trough angle is reduced from 90^o, the path becomes more tortuous and offers greater hydrodynamic resistance giving rise to high N_{TU} characteristics. A combination of different plates may be used to create an intermediate N_{TU} passage, which can be used to meet a specific N_{TU} requirement.

The plate pack is clamped together in a frame suspended from a carrying bar. Gaskets are fitted to seal the plate channels and interfaces. The frame consists of a fixed frame plate at one end and a moveable pressure plate at the other. The moveable plate facilitates access for cleaning or exchanging the heat transfer surfaces. A feature of this type of heat exchanger is the ability to add or remove surface area as necessary.

The plates are grouped into passes with each fluid being directed evenly between the paralleled passages in each pass. Whenever the thermal duty permits, it is desirable to use single pass, counter flow for an extremely efficient performance. Although plate and frame exchangers can accept more than two streams, this is unusual. Two-pass arrangements are, however, common. Figure 2.1.3 illustrates the flow path in such a unit.

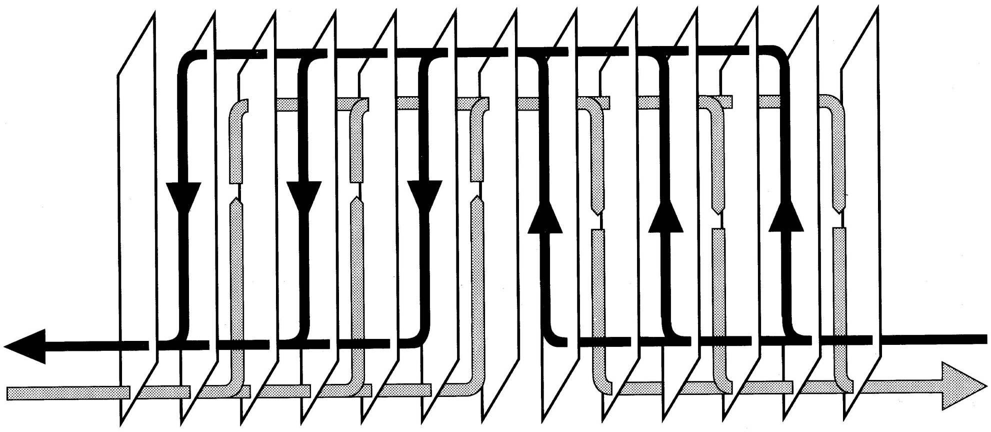

Figure 2.1.3 – A Two-Pass Plate and Frame Flow Arrangement

Plates can be produced from all pressable materials. The most common construction materials are:

- Stainless steel (AISI304, 316).
- Titanium.
- Incoloy.
- Hastelloy.

Where corrosion is a problem, some manufacturers offer plate and frame heat exchangers in non-metallic materials, such as a graphite/fluoroplastic composite or a polymer.

Usually the frame is made of coated mild steel, as it should not, under normal circumstances, come into contact with the process fluids. The surface coatings vary according to the exchanger environment. Frames can be stainless steel or clad with stainless steel as an alternative to mild steel.

Gasket properties have a critical bearing on the capabilities of a plate and frame heat exchanger, in terms of its tolerance to temperature and pressure.

Gaskets are commonly made of:

- Nitrile rubber.
- Hypalon.
- Viton.
- Neoprene.
- EPDM.

Originally, most manufacturers used glue to fix the gaskets to the plates. Several proprietary fixing techniques are available that eliminate the need to use glue, and most manufacturers have adopted these methods. These so-called 'glueless' gaskets are suitable for some heavy-duty industrial applications. The simplified removal and location of such gaskets can be beneficial, as it reduces downtime when on-site changing is necessary.

Care should be taken in locating the gaskets during reassembly, as imperfect sealing is the main disadvantage of the plate and frame heat exchanger.

Double-wall units are another variant catering for specific process situations. Here two special non-welded plates, fitted with a non-glued gasket to seal and hold the plates together, replace the single plate normally separating the two media. Consequently, two walls separate the product and service medium giving additional protection against cross contamination and the occurrence of a hostile reaction. The partially welded plate unit (see Section 2.1.2) is designed for handling aggressive media.

2.1.1.3 Operating Limits

The operating limits of gasketed plate and frame heat exchangers vary slightly from manufacturer to manufacturer. Typically, the operating temperature range of the metal plates is from -35°C to +200°C. Design pressures up to 25 bar can be tolerated, with test pressures to 40 bar.

Heat transfer areas range from 0.02 m^2 to 4.45 m^2 (per plate). Flow rates of up to 3,500 m^3/hour can be accommodated in standard units, rising to 5,000 m^3/hour with a double port entry. Approach temperatures as low as 1°C are feasible with plate and frame heat exchangers.

The surface pattern on the plates tends to induce good mixing and turbulence, and in general this type of heat exchanger has a low propensity for fouling. Fouling resistances of typically 25% of those for shell and tube heat exchangers have been measured by the Heat Transfer Research Incorporated (HTRI) in the USA.

Where fouling is a concern, the gap between the plates can be widened. For example, one manufacturer offers plates with a 13 mm gap and coarse contours for viscous liquids and fluids containing fibres, solids, crystals, pulp, etc.

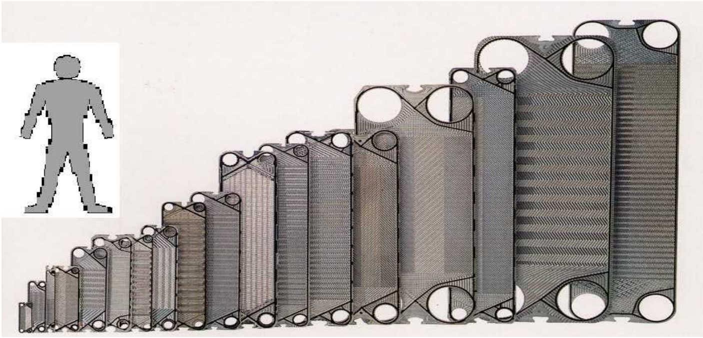

Figure 2.1.4 – Plate Heat Exchanger Plates
(Courtesy of APV)

2.1.1.4 Principal Applications

Gasketed plate and frame heat exchangers have a large range of applications typically classified in terms of the nature of the streams to be heated/cooled as follows:

- Liquid-liquid.
- Condensing duties.
- Evaporating duties.

Gasketed units may be used in refrigeration and heat pump plants (see also Section 2.1.3) and are extensively used in the processing of food and drinks, where the ease of plate cleaning and re-gasketting are important. In the chemicals sector, a substantial list of heating and cooling applications includes cooling isoparaffin, sulphuric acid, salt solutions, hexane and kerosene. Heating glycerine and condensing ethanol are other routine uses. The offshore chemical industry is also a large user in the UK.

There are potential applications for plate heat exchangers on most chemical plants. A typical process installation is shown in Figure 2.1.5.

Figure 2.1.5 – Process Application of a Plate and Frame Heat Exchanger
(Courtesy of APV)

2.1.1.5 Comparison with Shell and Tube Heat Exchanger

Figure 2.1.6 shows the comparative sizes of a shell and tube heat exchanger and a gasketed plate and frame unit of comparable duty. In quantitative terms, 200 m^2 of heat transfer surface requires a plate and frame heat exchanger approximately 3 metres long, 2 metres high and 1 metre wide. For a tubular heat exchanger achieving the same effect, some 600 m^2 of surface would be required in a shell 5 metres long and 1.8 metre in diameter, plus the extra length needed for tube bundle removal.

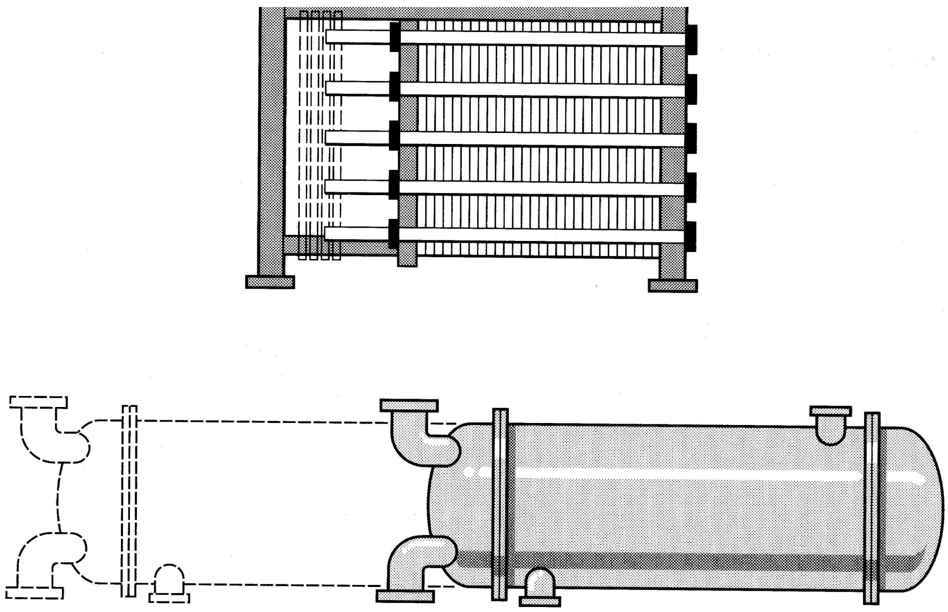

Figure 2.1.6 – Comparison of Shell and Tube and Gasketed Plate and Frame Heat Exchanger Sizes showing Maintenance Space Requirement

For liquid-liquid duties, surface area requirements are typically 25% of those of equivalent shell and tube units. Pressure drops for these duties are, on average, lower.

With regard to weight, the plate and frame unit shown in Figure 2.1.6 has an empty weight of 3.3 tonnes, that increases to 4 tonnes when filled with water. Comparable figures for the shell and tube heat exchanger are 6 tonnes and 11 tonnes respectively.

2.1.2 Partially Welded Plate Heat Exchangers

2.1.2.1 Introduction

Externally, partially welded plate heat exchangers or twin plate heat exchangers resemble a fully-gasketed plate and frame unit. However, the difference is the plate pack has alternating welded channels and gasketed channels as in the arrangement illustrated in Figure 2.1.7.

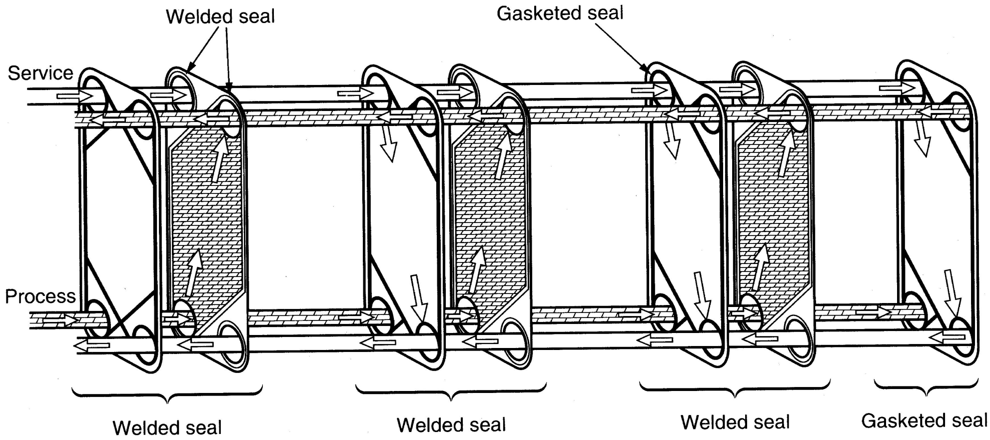

Figure 2.1.7 – Flow Diagram of the LR4 APV Baker Laser-Welded Plate Heat Exchanger (Courtesy of APV)

The advantage of welding the plate pairs is that, except for a small gasket around the ports, other materials are eliminated and corrosion is slightly reduced.

2.1.2.2 Construction

The overall construction is similar to that of the gasketed plate and frame heat exchanger (described in Section 2.1.1), with one important exception: each plate pair is welded together, normally using laser welding. Porthole gaskets fabricated from highly resistant elastomer or non-elastomer materials, are attached using a glueless method.

Plate construction materials are as for the gasketed plate and frame heat exchanger. The plate material is normally selected for its resistance to corrosion.

2.1.2.3 Operating Limits

As for the gasketed plate and frame type, but with the added protection from leaks afforded by the partially welded construction.

2.1.2.4 Principal Applications

As for gasketed plate and frame heat exchanger, but extended to include more aggressive media.

Partially welded plate heat exchangers are used for the evaporation and condensation of refrigerants such as ammonia and hydrochlorofluorocarbons (HCFCs), and for chemical and general process duties involving aggressive liquids.

2.1.2.5 Comparison with Shell and Tube Heat Exchanger

As for gasketed plate and frame units.

2.1.3 Brazed Plate Heat Exchangers

2.1.3.1 Introduction

The brazed plate heat exchanger (see Figure 2.1.8) consists of a pack of pressed plates brazed together, thus completely eliminating the use of gaskets. The frame can also be omitted.

Brazed plate heat exchangers tend to be offered by the principal suppliers of the plate and frame type and tend to be directed at niche markets such as refrigeration. These exchangers have heat transfer capabilities up to 600 kW, depending on the supplier.

The corrugated plates induce a highly turbulent flow such that the scouring action of the turbulence reduces surface deposits in the heat exchanger.

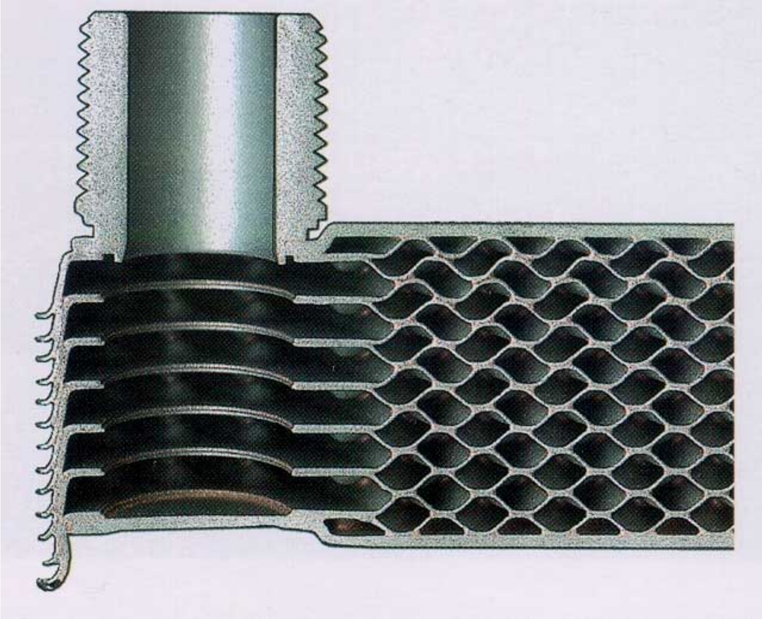

Figure 2.1.8 – Section Through a Brazed Plate Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

2.1.3.2 Construction

Brazed plate heat exchangers consist of a number of pressed stainless steel plates joined together by brazing. Typically a very high content copper braze is used, and the brazing process is carried out under vacuum. Capillary forces collect the brazing material at the contact points between the plates.

As well as sealing around the periphery of the plates, the internal herringbone contact points are also brazed, permitting higher pressures to be tolerated than in gasketed units.

Stainless steel is usually used as the plate material.

2.1.3.3 Operating Limitations

Copper brazed units are available for temperatures up to 225^{o}C and a maximum operating pressure of 30 bar, but copper braze may produce an incompatibility with some working media. Nickel brazed units are available for temperatures up to 400^{o}C and maximum operating pressures of 16 bar.

2.1.3.4 Principal Applications

The brazed plate unit is aimed at the refrigeration/heat pump market for evaporators and condensers (water-cooled), but it is also suitable for process water heating, heat recovery and district heating systems. Brazed plate heat exchangers can also be used as desuperheaters, subcoolers, economisers and oil coolers.

The introduction of nickel brazed units has allowed brazed units to be used within the process industries, for duties such as de-mineralised water cooling and solvent condensing.

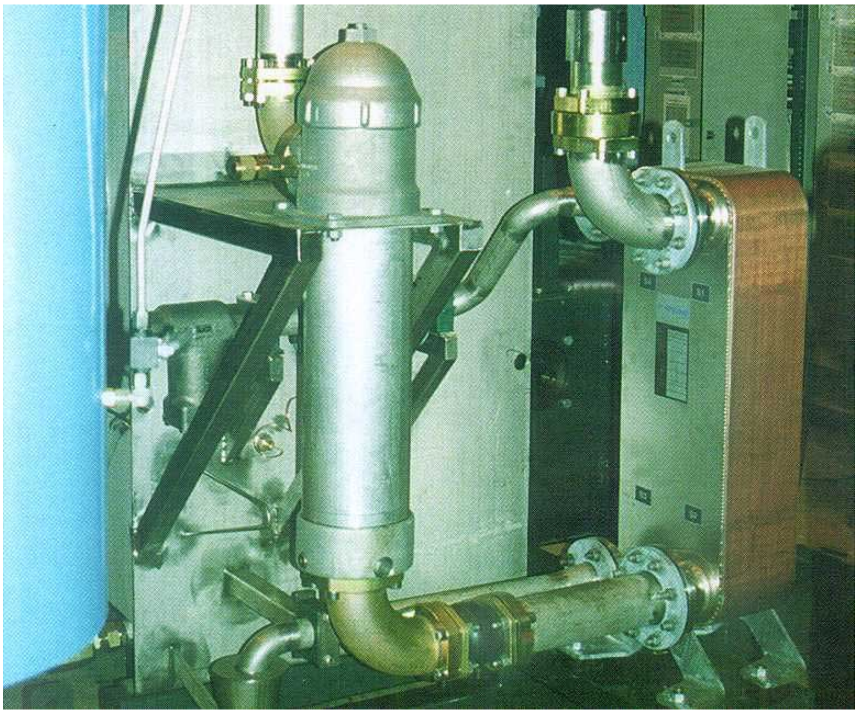

Figure 2.1.9 – A Brazed Plate Heat Exchanger Used as an Oil Cooler
(Courtesy of Alfa Laval Thermal Division)

2.1.3.5 Comparison with Shell and Tube Heat Exchanger

Typically, a brazed plate heat exchanger is about 20-30% of the weight of a shell and tube heat exchanger for the same duty.

For example, a brazed plate heat exchanger, used as a water-cooled refrigerant condenser with a duty of 70 kW, had a weight of 20 kg. Its height and width were 522 mm and 115 mm respectively. A conventional shell and tube condenser of the same duty would be 2,250 mm long, have a diameter of 200 mm, and weigh 130 kg.

2.1.4 The Bavex Hybrid Welded Plate Heat Exchanger

2.1.4.1 Introduction

The Bavex hybrid welded heat exchanger, made in the UK under licence from Bavaria Anlagenbau GmbH, is one of several welded plate units that have found a niche market as an alternative to a shell and tube heat exchanger, particularly where process conditions rule out the plate and frame configuration. The high-pressure capability and wide operating temperature range of the Bavex unit are particularly significant in this respect.

A unique feature of the Bavex design is its internal geometry. As explained below, both 'tube side' and 'plate side' flow paths can be identified.

2.1.4.2 Construction

The construction of a typical Bavex heat exchanger is illustrated in Figure 2.1.10.

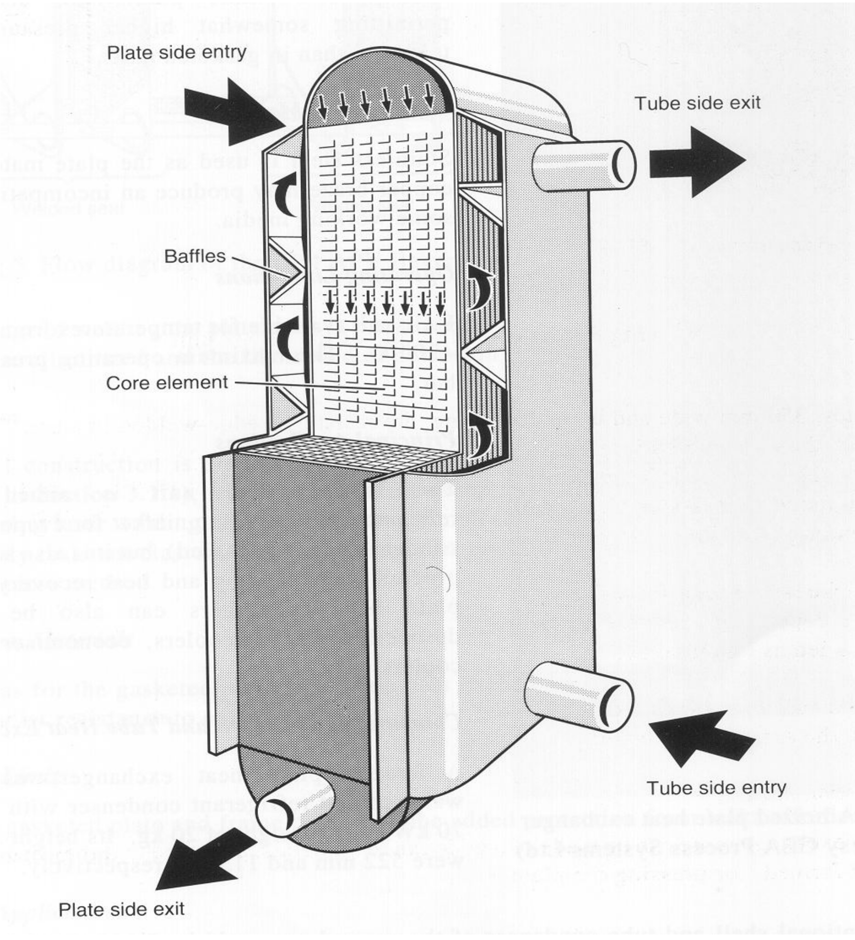

Figure 2.1.10 – Construction of a Bavex Welded Plate Heat Exchanger

The unit in Figure 2.1.10 employs multiple passes on the tube side and a single pass plate configuration. The core assembly is shown in Figure 2.1.11.

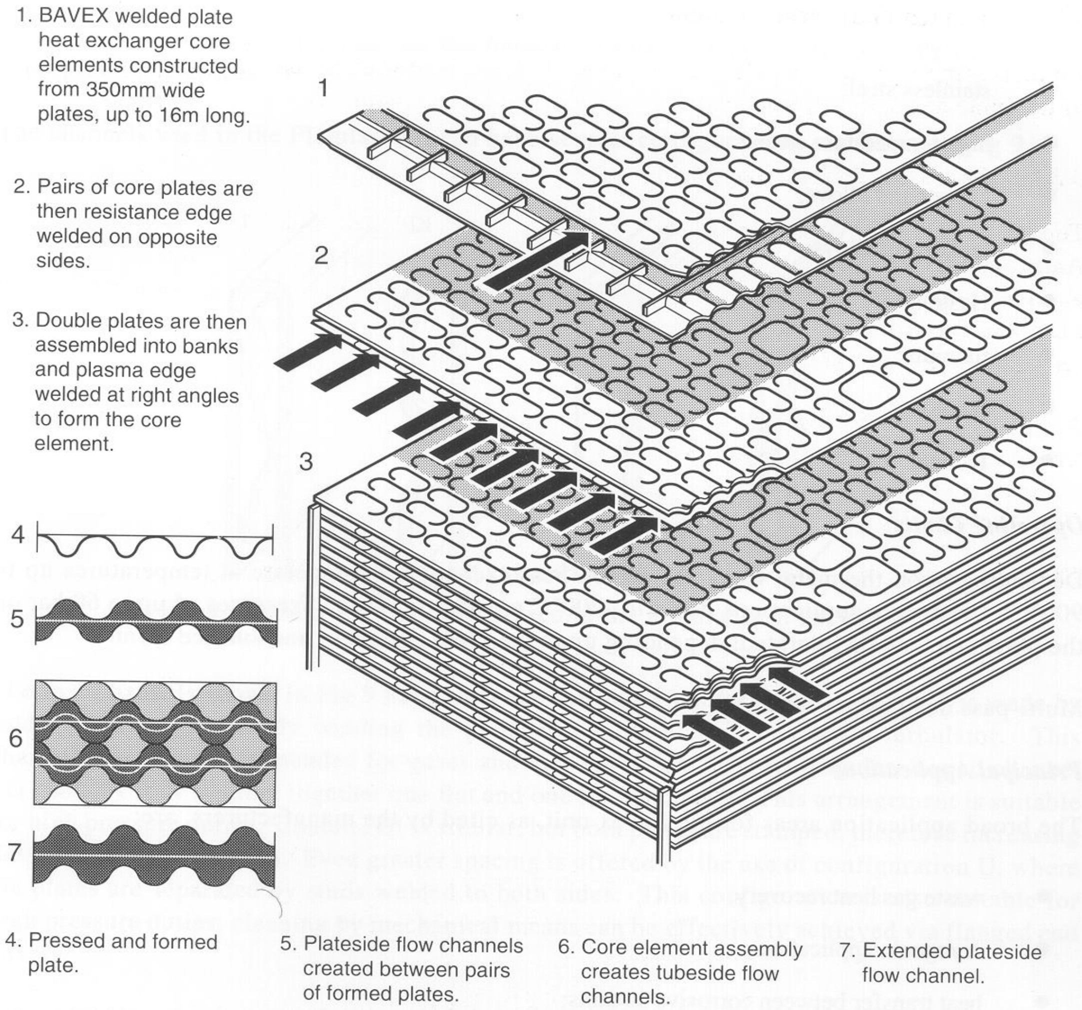

Figure 2.1.11 - Core Structure of a Bavex unit

The plates, 350 mm wide and up to 16 metres long, are resistance edge welded in pairs. The double plates are then assembled into banks and plasma edge welded at right angles to form the core element. The tube is 350 mm long, with up to 8,000 tubes per metre of cross-sectional area being accommodated. Cross-stamping occurs at 37 mm intervals; this induces turbulence in the tubes, while lending strength to the plates.

Plate thickness ranges from 0.2 to 1 mm, while the effective tube diameter ranges from 6.0 to 11.1 mm, depending upon the degree of pressing. The spacing of the plates on the 'plate' side can be varied as a function of the anticipated cleaning requirements.

The vessel containing the core may be of welded or flanged construction, the choice being partly based on the anticipated cleaning requirements.

The heat exchanger core can be made of a wide range of metals, provided that they can be welded and cold-formed (for pressing the plates).

Plate materials include:

- Stainless steel.
- High temperature steels.
- Copper and alloys.
- Nickel and alloys.
- Hastelloy.
- Titanium.
- Incoloy.
- Inconel.

2.1.4.3 Operating Limits

Depending upon the plate metal used, the Bavex heat exchanger can operate at temperatures up to 900°C. Cryogenic applications down to -200°C are also feasible. Pressures of up to 60 bar on the plate side can be tolerated, depending upon the plate thickness and surface form.

Multi-pass designs are feasible.

2.1.4.4 Principal Applications

The broad application areas for the Bavex unit are:

- Waste gas heat recovery.
- Cryogenic applications.
- Heat transfer between corrosive streams.
- Seawater applications.

Typical duties include recuperation (gas-gas) on incineration plant, distillation column condensers and liquid-liquid duties in chemicals and food processing.

2.1.4.5 Comparison with Shell and Tube Heat Exchanger

The Bavex unit is claimed to have typically 40% of the volume of an equivalent shell and tube heat exchanger. Heat transfer coefficients in liquid-liquid duties are about 5,000 W/m^{2}K.

2.1.5 The Platular Welded Plate Heat Exchanger

2.1.5.1 Introduction

The Platular heat exchanger, manufactured by Barriquand in France, is a welded plate type where standard plate thicknesses are used for the heat transfer surfaces. This gives the strength and integrity of a shell and tube design combined with the heat transfer coefficients of a plate. The plates are welded so no gaskets are necessary.

There are two variants of the design. The basic X type Platular eliminates a shell, while retaining headers and nozzles, by welding the plate elements longitudinally. This overcomes the need to incorporate devices to cope with the differential expansion between the shell and the core. Access is available for inspection and cleaning of the heat transfer surfaces.

In the S type Platular heat exchanger, cores are normally enclosed in a welded plate containment vessel - the 'shell'. Typically, there is no access to the plate pack although a recent innovation is to flange the plate pack to the shell so it is removable. Where both fluids are clean and it is not necessary to inspect the heat transfer surfaces, the plate pack in a shell is more cost competitive.

2.1.5.2 Construction

Three parameters govern the various construction options for the Platular heat exchanger. These are the form of the channels, the fluid flow configuration and whether a shell is used.

A shell design is used when all the fluids are clean. If one or more dirty fluids are anticipated the all-welded construction is used, including appropriate end covers enabling access for mechanical cleaning.

The channels used in the Platular unit can have several configurations, as shown in Figure 2.1.12.

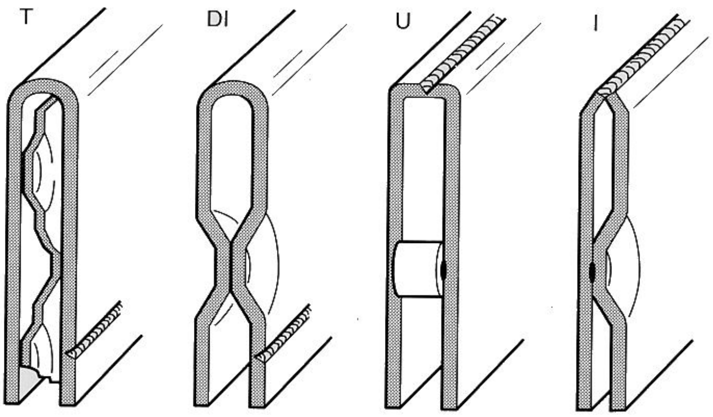

Figure 2.1.12 – Channel Configurations used in the Platular Heat Exchanger
(Courtesy of Barriquand Echangeurs)

The four channels shown in Figure 2.1.12 have what are known as 'contact points'. Type T is made by folding and longitudinally welding the plate, through which is inserted a turbulator. This channel design is recommended for gases and viscous fluids.

The rectangular-shaped channel I is made by spot welding together one flat and one stamped plate. This arrangement is suitable for high-pressure duties.

Channel DI is similar, but both plates are stamped, therefore increasing the spacing between them. Even greater spacing is offered by the use of configuration U, where the plates are separated by studs welded to both sides. This configuration is also suitable for high-pressure duties as cleaning by mechanical means can be effectively achieved via flanged end covers.

Where highly contaminated fluids, such as one carrying fibrous material, need to be handled, the manufacturers recommend a channel formed without contact points (see Figure 2.1.13). The spacing of this channel is independent of that employed on other circuits.

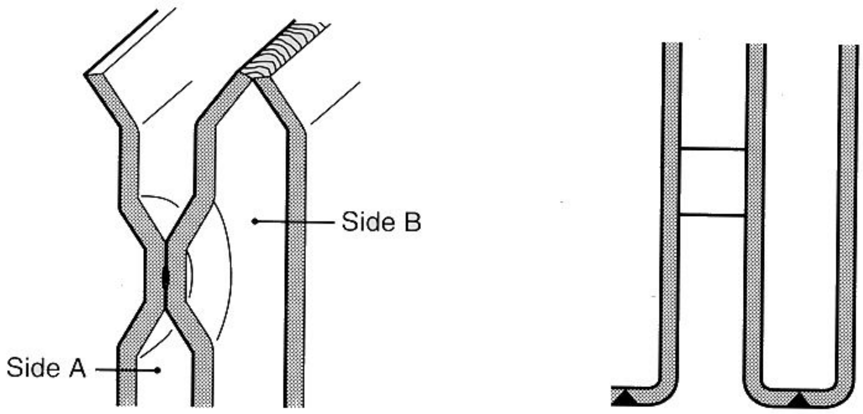

Figure 2.1.13 – Two Typical Channel Pairs
(Courtesy of Barriquand Echangeurs)

The Platular welded plate heat exchanger is available in:

- Most stainless steels.
- Hastelloy.
- Duplex.
- A variety of nickel-based alloys
- Titanium.

2.1.5.3 Operating Limits

Platular heat exchangers are suitable for use at temperatures between –180 and 700^{o}C and at pressures from full vacuum to 40 bar.

Multi-stream units up to a maximum of four streams can be constructed, and a mix of counter-current, co-current and cross-flow configurations can be accommodated. A multi-stream gas-gas unit is illustrated in Figure 2.1.14. Multiple passes can be incorporated at the design stage. Platular heat exchangers can be designed for two or more duties in the same unit, such as combining primary and secondary condensations.

Figure 2.1.14 – A Typical X Type Platular Exchanger Showing Access Doors to the Heat Transfer Surfaces (Courtesy of Barriquand Echangeurs)

A range of units up to those suitable for multi-MW duties is available. The amount of heat transfer surface in a single unit can be up to 1,500 m^2.

Construction can conform to standards such as BS, CODAP, STOOMWEZEN, TUV and ASME, depending on the user's specification.

2.1.5.4 Principal Applications

Generic heat exchange duties for Platular units are:

- Gas-gas.
- Gas-liquid.
- Liquid-liquid.
- Condensers.
- Evaporators.

Platular welded plate heat exchangers are used in the chemical, food and drink, paper, cement, and refrigeration industries.

A typical duty would be heat recovery on a cold box employing a multi-pass, multi-stream configuration. In one such unit at a Rhone-Poulenc plant in France, 336 m^2 of surface was used to simultaneously heat three gas streams - hydrogen, carbon monoxide and methane from 2°C to 32.2°C using gas at 34°C, which was cooled to 6.5°C. Mass flow of gas on the hot side was 6,666 kg/hour and close approach temperatures were achieved.

2.1.5.5 Comparison with Shell and Tube Heat Exchanger

Based on the manufacturer's data, the overall 'U' values are 2 to 4 times those achievable in conventional shell and tube units, resulting in typical volume reductions of 75 - 90%. Therefore, equivalent plant space required is very much less and no additional space is required for tube bundle removal.

Turbulent flow conditions reduce fouling and full counter-current operation can achieve close temperature differences.

2.1.6 The Compabloc Welded Plate Heat Exchanger

2.1.6.1 Introduction

Another version of the welded plate heat exchanger is the Compabloc unit manufactured by Alfa Laval Thermal.

Compabloc heat exchangers are targeted on typical shell and tube, spiral, and plate and frame heat exchanger applications and also applications with gasket compatibility problems. The absence of gaskets enables it to handle high temperature fluids and operate in chemically aggressive environments. Also, the totally bolted design of Compabloc allows quick disassembly of the frame to access the plate-pack for cleaning, maintenance, repair or replacement.

2.1.6.2 Construction

In the Compabloc single-pass design, sets of pressed plates are automatically welded together to give a cross-flow configuration. A multi-pass unit is globally counter-current. The number of plate sets is determined by the required size of the pack. Column liners (see Figure 2.1.15) are then welded on at all four corners and the plate pack is completed by welding top and bottom plate liners. Typically, the gap between the plates is 5 mm.

Four machined columns (see Figure 2.1.15) are welded to the bottom machined head, and the plate pack is slid over the columns. The top plate is then located and welded to each column. Adjustable baffles are installed as required for the desired even number of passes, the baffles also being of the same material as the pack.

The final stage of assembly involves bolting on connections for cover plates, with or without alloy liners, into the columns and heads of the panels.

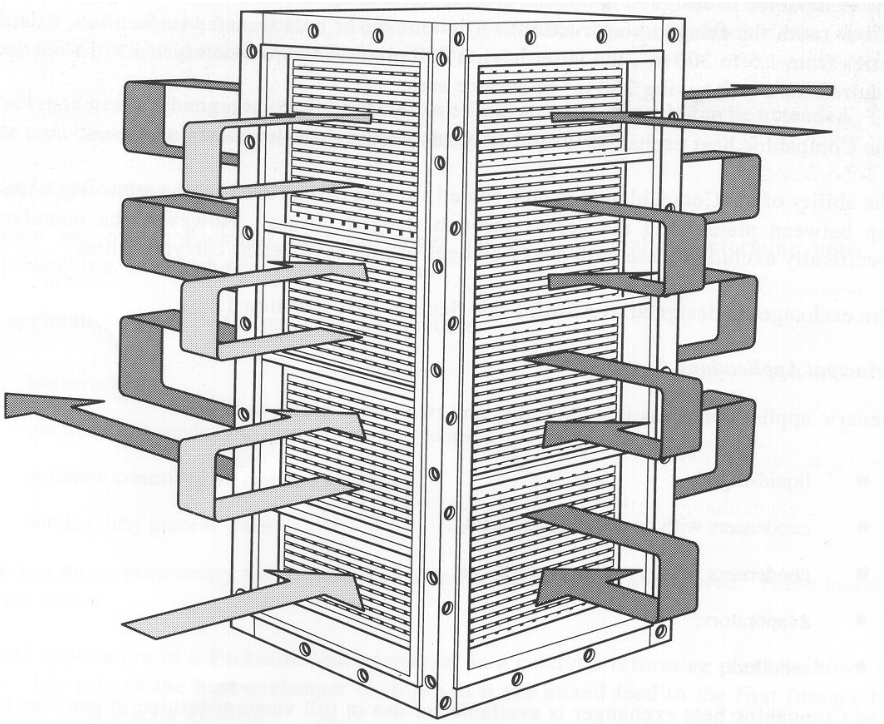

Figure 2.1.15 – Construction of the Compabloc Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

The Compabloc design is available in the following materials:

- Stainless-steel 316L.
- Titanium and titanium plus 0.2% palladium.
- Hastelloy C-276, C-22, B and C.
- Avesta 254 SMO.
- UranusB-6.
- Incoloy 825.
- Monel.
- Tantalum.

Baffle assemblies and panel liners are available in the same material as the plates. Connections are available in steel or alloy materials.

2.1.6.3 Operating Limits.

The Compabloc exchanger is designed to operate at temperatures up to 300°C and working pressures up to 32 bar (with the flanged construction). The amount of heat transfer surface in a Compabloc exchanger varies from 1.5 to 300 m^2, the latter having 500 plates. Approximately 1 m^2 of floor space is required for a unit having 300 m^2 of surface area.

Compabloc heat exchangers are normally designed to handle two fluid streams. In single-pass with cross-flow the Compabloc is capable of handling low N_{TU} duties. N_{TU}, the number of transfer units, is:

$$N_{TU} = \frac{UA}{\left(\dot{M}C_p\right)_{smaller}}$$

In multi-pass with global counter-current flow, temperature-cross is easily achieved.

The ability of the Compabloc design to handle fouled streams is improved by the relatively wide 5 mm gap between plates, and the access through flanged covers. However, the manufacturers specifically exclude its use with heavy sludges or process streams carrying fibres.

Figure 2.1.16 – Compabloc Heat Exchanger (Courtesy of Alfa Laval Thermal Division)

2.1.6.4 Principal Applications

Generic application areas include liquid and two-phase duties such as:

- Liquid-liquid.
- Condensers with or without subcooling.
- Condensers with or without inserts.
- Evaporators.
- Reboilers.

The Compabloc heat exchanger is available for use in full vacuum service; it can also be used with refrigerants.

2.1.7 The Packinox Welded Plate Heat Exchanger

2.1.7.1 Introduction

Packinox is a fully owned subsidiary of Framatome who design, develop and fabricate large, heavy duty welded plate heat exchangers for new units and de-bottlenecking refurbishments in the refining, gas processing and petrochemicals industries.

2.1.7.2 Construction

The Packinox design is based on corrugated stainless steel sheets that are explosion formed underwater. Plates are welded together to form the plate bundle, which is inserted into a pressure vessel.

Depending on the application, Packinox heat exchangers may not require a shell; in this case, the bundle may be inserted directly into a column or placed between heavily bolted panels, as in gasketed plate and frame heat exchangers.

When a shell is fitted, bellows are required to compensate for the differential expansion between the vessel and plate bundle. The bellows are located inside the shell, between the bundle and the pipes connected to the nozzles as shown in Figure 2.1.17. The flow paths are counter-flow.

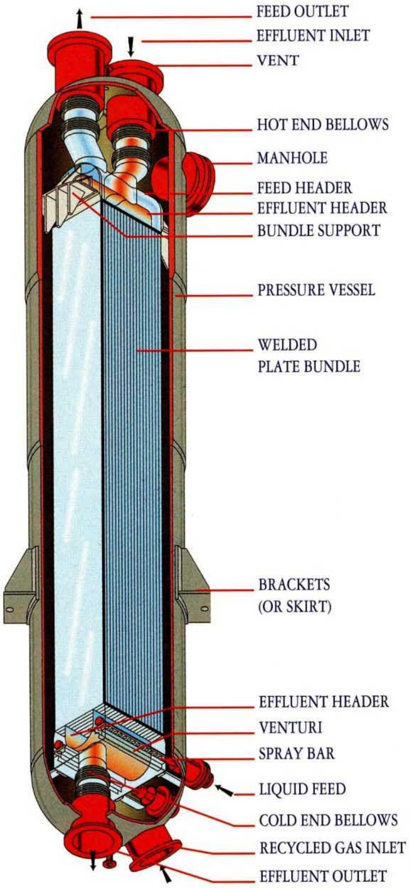

Figure 2.1.17 – Packinox Compact Heat Exchanger (Courtesy of Packinox)

Fabrication materials include:

- All types of austenitic stainless steel.
- Titanium.
- Highly corrosion resistant 6 Mo austenitic stainless steel.

2.1.7.3 Operating Limits

Operating ranges are a function of the plate and shell materials used, but the Packinox can operate at temperatures between -200^{o}C and +700^{o}C. Plate flexibility make these heat exchangers able to withstand large temperature differences between feed and effluent.

Fluid pressure can be extremely high; the only limits on design pressure being the same as those of the containment vessel. Absolute pressures of up to 300 bar can be tolerated normally in the shell.

Substantial differential pressure resistance can be reached due to the multitude of corregation-to-corregation contact points between plates. Differential pressures of up to 60 bar are readily accommodated, with a possible extension to 100 bar.

Packinox heat exchangers normally handle two fluid streams, but can also be multi-fluid.

Homogeneous flow distribution and 100% liquid feed entrainment is ensured for two-phase fluids, even at low operating pressures, either through spray bars or through a patented two-phase fluid distributor, depending on the gas-to-liquid ratio.

The surface area of a single Packinox unit can be as high as 16,000 m^2.

2.1.7.4 Principal Applications

Packinox is the industry standard in catalytic reforming units, and is used in such applications as paraxylene, hydrotreating and isomerization. Packinox heat exchangers operate in a wide variety of chemical processes including linear alkyl benzene, styrene and methanol.

Other applications include combined feed heat exchangers, temperature controlled reactors, multi-fluid exchangers/liquid-vapour separators for gas dew point control and condensate recovery, in-column reflux condensers and stab-in reboilers.

A typical application of a Packinox heat exchanger in a catalytic reforming plant is shown in Figure 2.1.18. The role of the heat exchanger is to pre-heat the mixed feed to the first furnace by cooling the final reactor effluent.

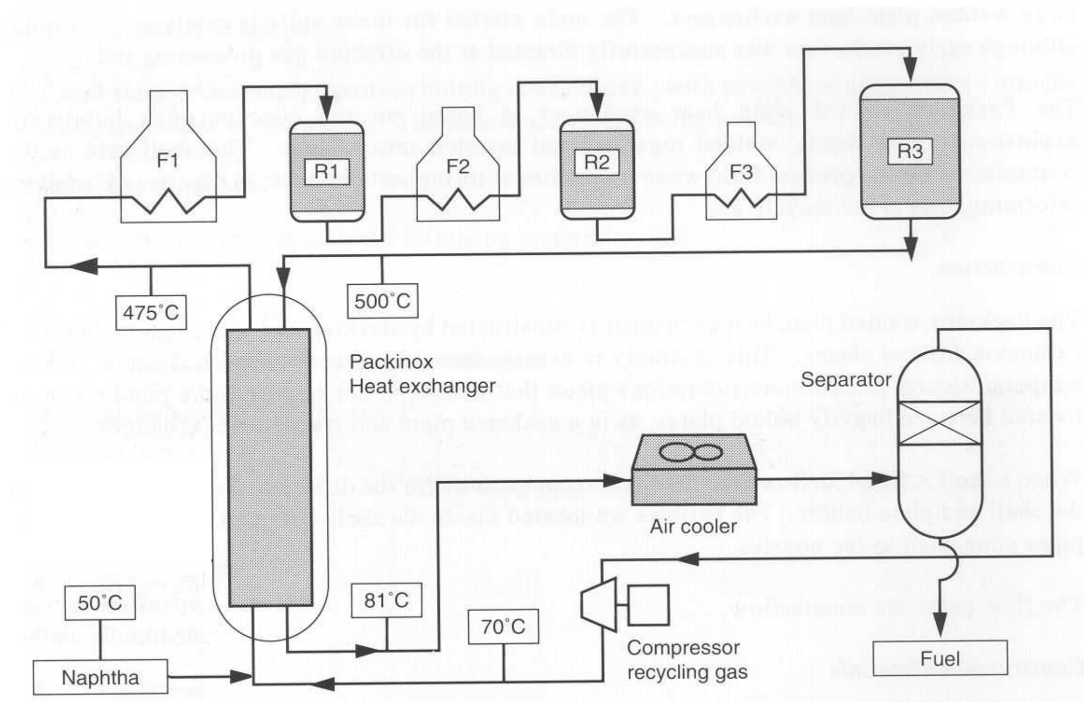

Figure 2.1.18 – A Packinox Plate Heat Exchanger in a Catalytic Reforming Plant (Courtesy of Packinox)

2.1.7.5 Comparison with Shell and Tube Heat Exchanger

For example, in a gas cooling loop handling 1.5 million m^3/day of gas at 39 bar and with the heat exchanger train located downstream of the gas dehydration unit, a shell and tube heat exchanger train would cool the gas to -24^{o}C with a duty of 84 MW. The cold approach would be 14^{o}C and the LMTD 7.4^{o}C.

A shell and tube heat exchanger train would involve eight shells with a total weight of 1,300 tonnes. A Packinox exchanger for the same conditions would require two shells with a total weight of 260 tonnes. The saving on 'footprint' would be 200 m^2.

Another example of how much a welded plate heat exchanger is lighter in weight and more compact than tubular designs for the same duty, as well as offering improved thermal and hydraulic efficiency, is shown in Figure 2.1.19.

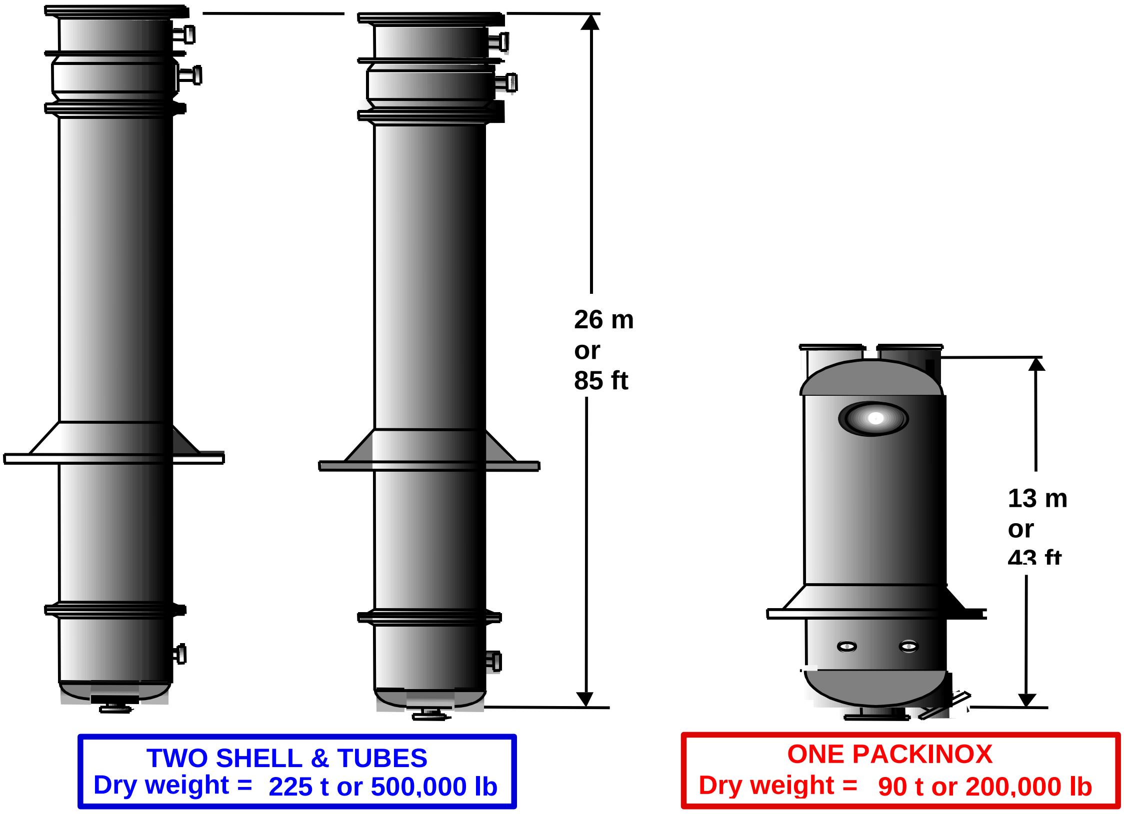

Figure 2.1.19 – Size and Weight Comparison for the Same Duty
(Courtesy of Packinox)

2.1.8 The AlfaRex Welded Plate Heat Exchanger

2.1.8.1 Introduction

The AlfaRex heat exchanger was the first full-size, gasket-free heat exchanger. The herringbone plate design creates channels with high fluid turbulence that increases thermal efficiency and minimises the risk of fouling.

Media flow is counter-current which is optimal for heat transfer, particularly in heat recovery duties. Per unit of surface area, counter current flow achieves 20% higher heat transfer values than cross flow.

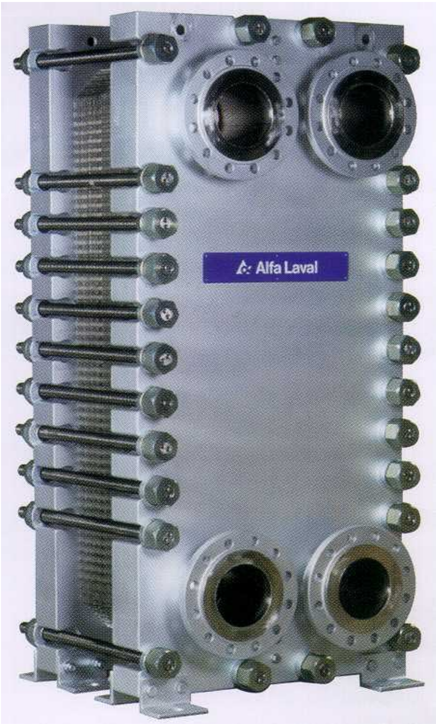

Figure 2.1.20 – AlfaRex Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

2.1.8.2 Construction

Plates with the traditional herringbone pattern are laser-welded together to form a plate pack in which both media are in full counter-current flow.

Plate materials include:

- AISI 316.
- SMO.
- Titanium.
- Palladium-stabilised Titanium.
- Hastelloy C276.
- Nickel.

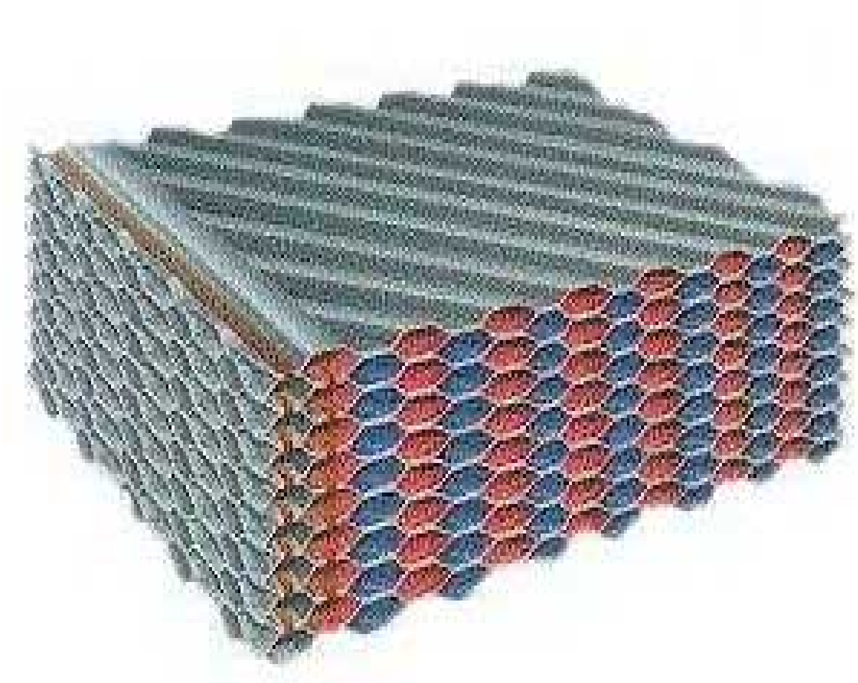

Figure 2.1.21 – Cross-section through AlfaRex Welded Plate Pack
(Courtesy of Alfa Laval Thermal Division)

2.1.8.3 Operating Limits

The AlfaRex design operating temperature range is -50^{o}C to +350^{o}C at pressures up to 40 bar. The exchanger is capable of handling flowrates up to 800 m^3/hour.

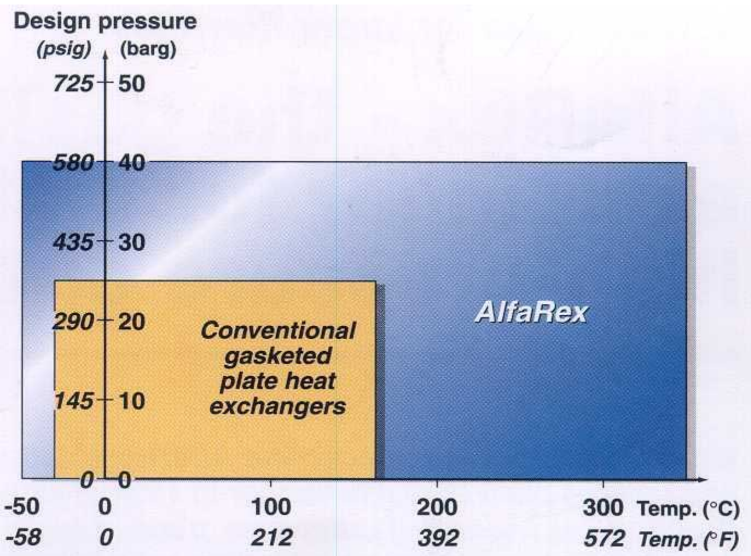

Figure 2.1.22 - Operating Ranges for the AlfaRex and Conventional Gasketed Plate Exchangers (Courtesy of Alfa Laval Thermal Division)

2.1.8.4 Principal Applications

Typical duties for the AlfaRex heat exchanger are:

- Offshore Platforms
  - Cooling of hydrocarbon gas, condensate and crude oil.
  - Heating of condensate and crude oil.
  - TEG interchanging.
- Caustic Soda Production
  - Heating and cooling duties in the evaporation of sodium hydroxide.
- Petrochemical Industries
  - Production of various chemicals, such as caprolactum, ethylene oxide and polyols.
  - Solvent recovery.
  - Reactor temperature control and batch heating.
  - Steam applications.
- Vegetable Oil Refining
  - Interchanging, heating and cooling of high temperature oil in deodorisation and hydrogenation.
- Refrigeration
  - Evaporation and condensing of ammonia or carbon dioxide in heat pump and adsorption systems.
- Power Plants
  - Pre-heating of feedwater.
- District Heating.

2.1.8.5 Comparison with Shell and Tube Heat Exchanger

The AlfaRex heat exchanger uses less than 20% of the floor-space and is only 20% of the weight of the shell and tube heat exchanger for the same duty. Due to the optimal counter-current flow design, the AlfaRex can perform the same heat duty with a reduced transfer area and therefore at less cost.

Also, the reduced hold-up volume allows more accurate process control and improves operational safety when handling hazardous media.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.2

PLATE-FIN HEAT EXCHANGERS

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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2.2.2.2 Construction
2.2.2.3 Operating Limits
2.2.2.4 Principle Applications
2.2.2.5 Comparison with Shell and Tube Heat Exchanger

2.2.3 Diffusion-Bonded Plate-Fin Heat Exchangers
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PLATE-FIN HEAT EXCHANGERS

2.2.1 Introduction

Plate-fin heat exchangers are a matrix of flat plates and corrugated fins in a sandwich construction.

Brazed aluminium plate-fin heat exchangers exhibit certain features and characteristics that distinguish them from other types of heat exchanger.

These include:

- A very large heat transfer area per unit volume of heat exchanger. This surface area is composed of primary and secondary (finned) surfaces. Typically, the effective surface area is over five times greater than that of a conventional shell and tube heat exchanger. Area densities range from 850 to 1,500 m^2/m^3.
- A single heat exchanger can incorporate several different process streams and the unique plate-fin construction allows these to enter/exit the exchanger at intermediate points along the exchanger length rather than just at the ends.
- Very close temperature approaches between streams (typically 1 to 3°C) can be accommodated leading to operational cost savings.
- High thermal efficiency, use of aluminium and multi-stream capability combine to form a compact, low-weight structure.
- Usually plate-fin exchangers operate at cryogenic temperatures. Therefore the exchanger is housed in an insulated "cold-box" (typically carbon steel) to preserve the cold. Alternatively, a locally applied exterior insulant may be used.

The versatility of plate-fin heat exchangers, coupled with the ability to manufacture them in a variety of other materials, makes them ideal for a range of process duties outside the cryogenics field.

2.2.2 Brazed Plate-Fin Heat Exchangers

2.2.2.1 Introduction

This section describes brazed plate-fin heat exchangers, an example of which is pictured in Figure 2.2.1.

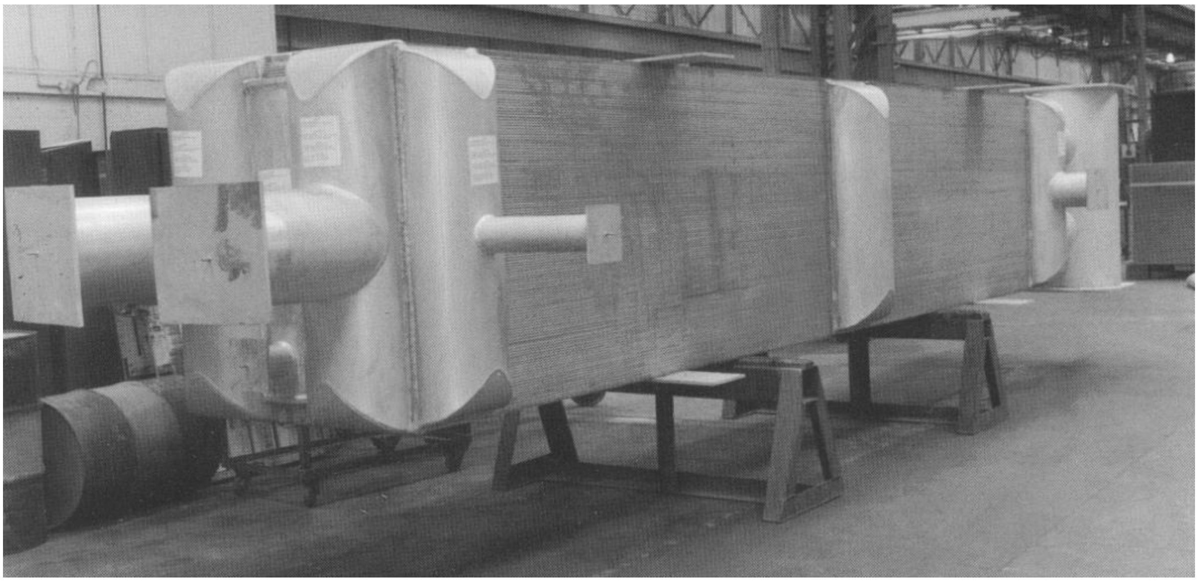


Figure 2.2.1 – Aluminium Plate-Fin Heat Exchanger
(Courtesy of Chart Marston Limited)

2.2.2.2 Construction

The heat exchanger is assembled from a series of flat sheets and corrugated fins in a sandwich construction. Tube plates (i.e. parting sheets) provide the primary heat transfer surface. Tube plates are positioned alternatively with the layers of fins in the stack to form the containment between individual layers. These elements are built into a complete core and then vacuum brazed to form an integral unit. A section through a typical plate-fin heat exchanger core is shown in Figure 2.2.2.

The heat transfer fins provide the secondary heating surface for heat transfer. Fin types, densities and heights can be varied to ensure that exchangers are tailor-made to meet individual customer requirements in terms of heat transfer performance versus pressure drop.

Distributor fins collect and distribute the heat transfer fluid from the header tank to the heat transfer fins at the inlet and reverse the process at the outlet. Distribution fins are taken from the same range as the heat transfer fins, but tend to be less dense.

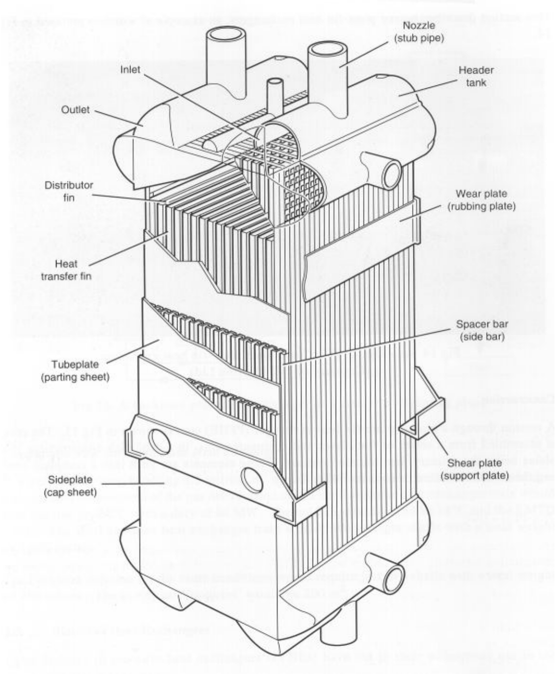


Figure 2.2.2 – Core Structure of a Brazed Aluminium Plate-Fin Heat Exchanger
(Courtesy of Chart Marston Limited)

The heat exchanger core is then encased in a welded structure that incorporates headers, support plates and feed/discharge pipes.

Most plate-fin heat exchangers are made of aluminium, with a vacuum-brazed core. Corrosion-resistant and heat-resistant brazing alloys can be used; for example plate-fin heat exchangers can also be assembled in stainless steel, a variety of nickel-based alloys, and some other specialist alloys. A stainless steel unit is shown in Figure 2.2.3.

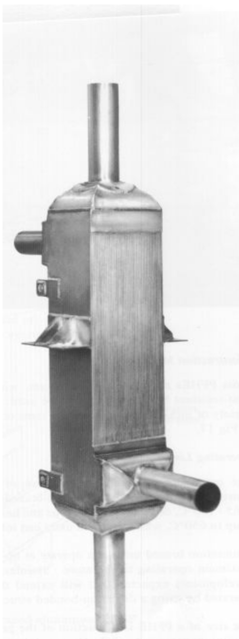


Figure 2.2.3 – Stainless Steel Plate-Fin Heat Exchanger
(Courtesy of Chart Marston Limited)

2.2.2.3 Operating Limits

The maximum operating temperature of a plate-fin heat exchanger is a function of its construction materials. Aluminium brazed plate-fin heat exchangers can be used from cryogenic temperatures (-270°C) up to 200°C, depending on the pipe and header alloys. Stainless steel plate-fin heat exchangers are able to operate at up to 650°C, while titanium units can tolerate temperatures approaching 550°C.

Aluminium brazed units can operate at up to 120 bar, depending on the physical size and the maximum operating temperature. Stainless steel plate-fin heat exchangers are currently limited to 50 bar, with developments expected that will extend the capability to 90 bar. Higher pressures can be tolerated by using a diffusion-bonded structure (see Section 2.2.3).

The size of a plate-fin heat exchanger is a function of the procedure used to assemble the core. In the case of aluminium vacuum-brazed units, modules of 6.25 m x 2.4 m x 1.2 m are available.

When selecting brazed aluminium plate-fin exchangers, the engineer should ensure that:

- All fluids must be clean and dry. Filtration must be used to remove particulate matter over 0.3mm.
- Fluids must be non-corrosive to aluminium. Water is suitable if it is a closed loop and contains corrosion inhibitors.
- Fluids must be in the temperature range –270 to +200°C.
- The maximum design pressure is less than 120 bar.

Fin Type	**Application**	**Features**	
		Relative Δp	**Relative Heat Transfer**
Plain	General	Lowest	Lowest
Perforated	Boiling streams	Low	Low
Herringbone	Gas streams with low allowable ΔP High pressure streams Gas streams for hydrocarbon and natural gas applications	High	High
Serrated	Gas streams in air separation applications General	Highest	Highest

Table 2.2.1 – Brazed Plate-Fin Types

2.2.2.4 Principal Applications

The plate-fin heat exchanger is suitable for use over a wide range of temperatures and pressures for gas-gas, gas-liquid and multi-phase duties. Typically, these involve:

- Chemical and petrochemical plant:
  - Corrosive and aggressive chemicals.
  - Ammonia and methanol plant.
  - Ethylene and propylene production.
  - Oxygen plant.
  - Inert gas recovery.
  - Hydrogen plant.

- Hydrocarbon off-shore applications:
  - Compressor coolers.
  - Fuel processing and conditioning plant.

- Miscellaneous applications:
  - Fuel cells.
  - Heat recovery plant.
  - Pollution control systems.

In addition to the typical gas/gas applications e.g. in gas liquefaction processes, plate-fin heat exchangers are increasingly used in the following two generic applications:

- Dephlegmators

  A dephlegmator is a refluxing heat exchanger used for partially condensing/purifying fluids in applications such as ethylene recovery and hydrogen purification. The heat exchanger arrangement is shown in Figure 2.2.4.

  The feed stream requiring purification is typically a low molecular weight gas containing small amounts of heavier components. The partially cooled feed stream enters the plate-fin heat exchanger at point A and is cooled by the separate refrigerant stream, and a third process steam (E-F). The plate-fin heat exchanger is mounted vertically, so that the feed gas cools as it flows upwards. The condensate then runs back against the gas flow, where mass transfer (rectification) takes place.

- Compact kettle reboilers

  The use of plate-fin heat exchanger cores as the basis of kettle reboilers, as shown in Figure 2.2.5, permits considerable size reductions compared to conventional shell and tube reboilers. As well as the thermal advantages, the plate-fin heat exchanger-based unit exhibits a lower liquid carry-over, mechanical joints are eliminated, and core removal for repair or replacement is facilitated.

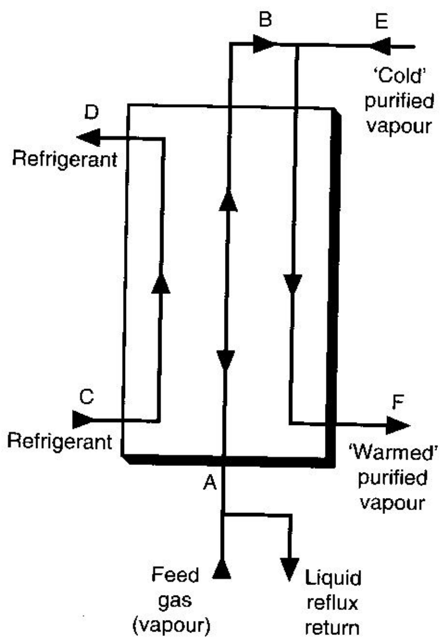


Figure 2.2.4 – Plate-Fin Heat Exchanger Dephlegmator Arrangement

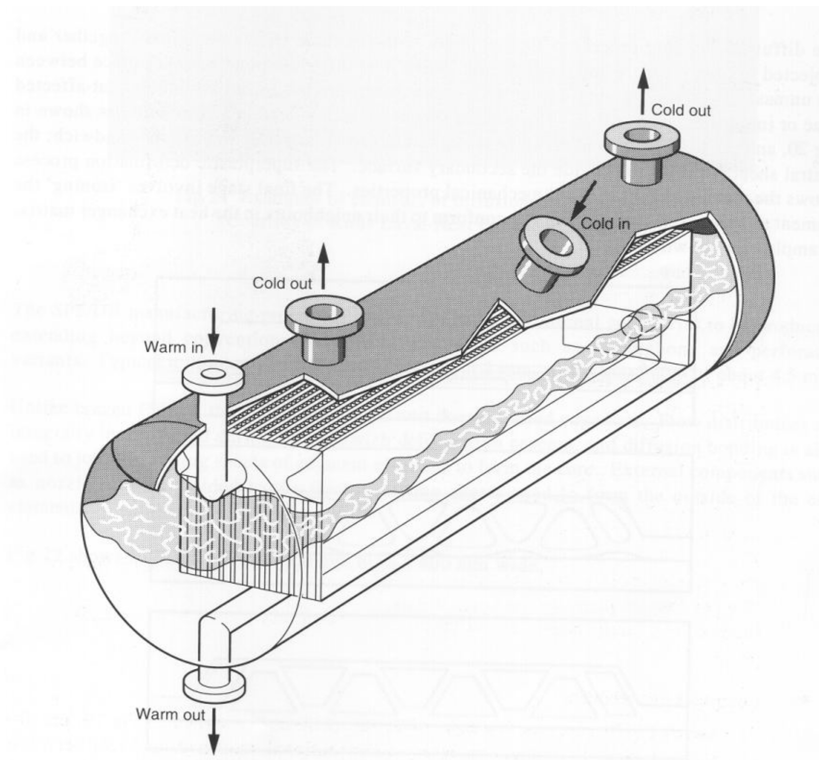


Figure 2.2.5 – The Use of an Aluminium Plate-Fin Heat Exchanger as the Core of a Kettle Reboiler

Plant Types	Products and Fluids	Typical Temperature Range (°c)	Typical Pressure Range (bar.g)
Industrial Gas Production - Air Separation - Liquefaction	Oxygen Nitrogen Argon Rare Gases Carbon Dioxide	-200 to +65	1 to 60
Natural Gas Processing (NGP) - Expander Type - Nitrogen Rejection Unit (NRU) - Liquefied Petroleum Gas (LPG) - Helium Recovery	Methane Ethane Propane Butane Pentane Nitrogen Helium Hydrogen Hexane Carbon Dioxide	-130 to +100	15 to 100
Liquefied Natural Gas (LNG) - Base Load - Peakshaver	Liquefied Natural Gas Multi-component refrigerants	-200 to +65	5 to 75
Petrochemical Production - Ethylene - MTBE - Ammonia - Refinery Off-Gas Purification	Ethylene Propylene Ethane Propane MTBE Ammonia Carbon Monoxide Hydrogen	-200 to +120	1 to 100
Refrigeration Systems - Cascade Cooling - Liquefaction	Helium Freon Propane Ethylene Propylene Nitrogen Hydrogen Multi-component Refrigerants	-270 to +100	15 to 45

Table 2.2.2 – Typical Applications of Brazed Plate-Fin Heat Exchangers

2.2.2.5 Comparison with Shell and Tube Heat Exchanger

A plate-fin heat exchanger with 6 fins/cm provides approximately 1,300 m^2 of surface per m^3 of volume. This heat exchanger would be approximately 10% of the volume of an equivalent shell and tube heat exchanger with 19 mm tubes.

2.2.3 Diffusion-Bonded Plate-Fin Heat Exchangers

2.2.3.1 Introduction

Diffusion bonding has a number of advantages over brazing when assembling a compact heat exchanger. As discussed in Section 2.2.2, most plate-fin heat exchangers still use brazing to assemble the core, with aluminium as the principal core material.

Recently, Rolls Laval Heat Exchangers Ltd applied a technique used for the cost-effective manufacture of aero-engine components -superplastic forming/diffusion bonding (SPF/DB) to the construction of plate-fin heat exchangers. This process permits titanium, and potentially stainless steel, plate-fin heat exchangers of high integrity to be manufactured, giving superior strength characteristics and enhanced corrosion resistance.

2.2.3.2 Construction

The formation of the basic element in the Rolls Laval titanium plate-fin heat exchanger, i.e. two parting sheets separated by the secondary surface, involves several stages. Starting with well-prepared titanium sheets, a bond inhibitor is deposited on the internal surfaces of the parting sheets such that diffusion bonding only occurs where required between the two sheets (as in roll-bonding) and the third sheet, which forms the secondary surface.

The diffusion bonding process is then applied, with the three sheets being held together and subjected to high pressure and temperature. Solid state diffusion bonding takes place between the unmasked surfaces, giving a joint with parent metal properties but without a heat-affected zone or impurities such as flux. The bonded sheets are then placed in a closed die, and controlled internal pressure is applied to superplastically deform the sandwich. The central sheet stretches to provide the secondary surface as shown in Figure 2.2.6. The super-plastic deformation process allows the metal to retain its good mechanical properties. The final stage involves 'ironing' the element to ensure flat surfaces that can conform to their neighbours in the heat exchanger matrix. Examples are shown in Figure 2.2.7.

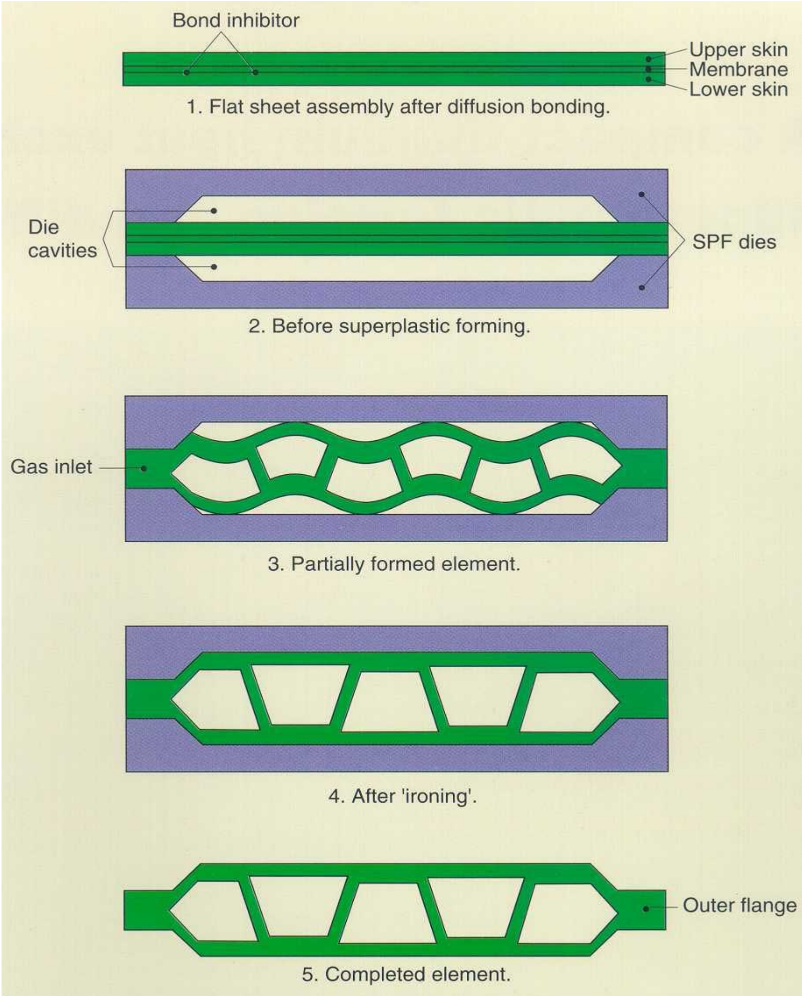


Fig 2.2.6 – Manufacturing the Core of a Diffusion-Bonded Plate-Fin Heat Exchanger (Courtesy of Rolls Laval Heat Exchangers Ltd)

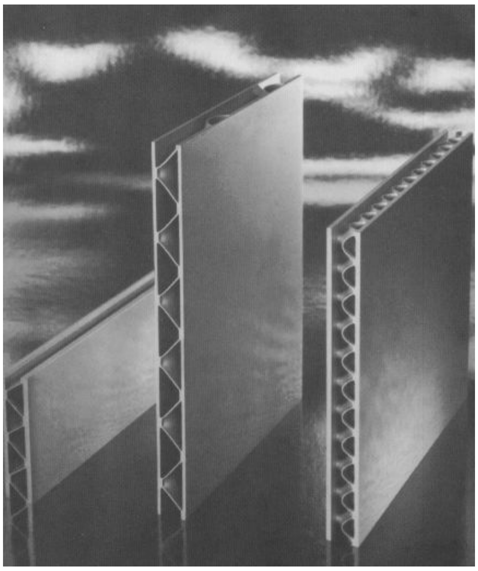


Figure 2.2.7 – Example Elements of Diffusion Bonded Plate-Fin Heat Exchangers (Courtesy of Rolls Laval Heat Exchangers Ltd)

The SPF/DB manufacturing process allows a wide range of internal geometries to be produced, extending beyond conventional finning arrangements such as herringbone and perforated variants. Typical minimum channel heights are about 2 mm, with a maximum of about 5 mm.

Unlike brazed plate-fin heat exchangers, the diffusion-bonded unit does not need edge bars. Flow distributors are integrally incorporated during the sandwich deformation process.

Modules of up to 41 elements are formed by diffusion bonding the parting sheets of adjacent elements. The modules are then joined at the stream inlets and outlets to form an exchanger block of the required size, to which the headers, nozzles and other external features are welded. Figure 2.2.8 shows a completed unit of 8 modules, each of which is 2 m high and 1 m wide.

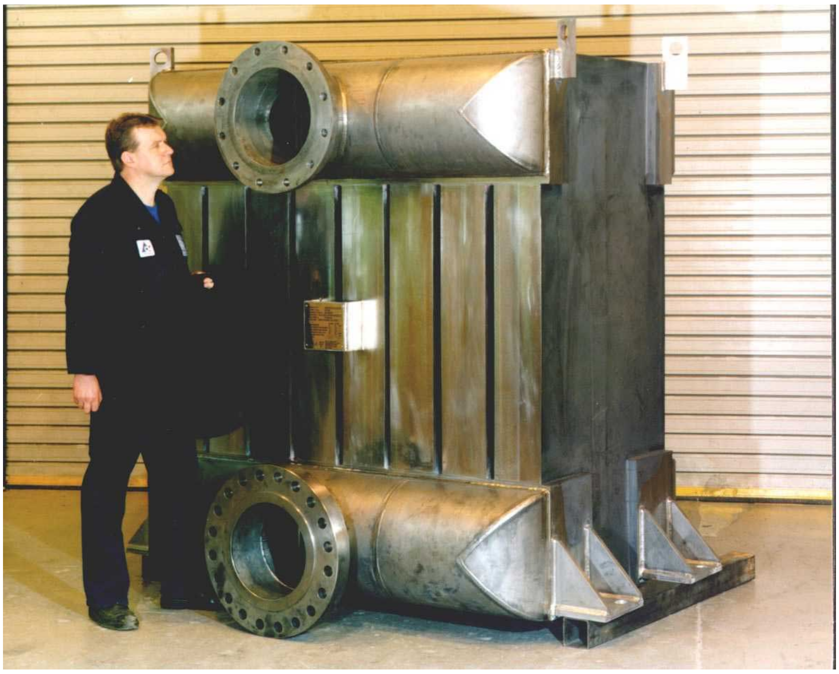


Figure 2.2.8 – A Diffusion-Bonded Titanium Plate-Fin Heat Exchanger
(Courtesy of Rolls Laval Heat Exchangers Ltd)

The diffusion-bonded plate-fin heat exchangers currently available are constructed using titanium. Several other commercially significant alloys exhibit super-plasticity, and the technique can be developed for use with both stainless steel and nickel alloys.

2.2.3.3 Operating Limits

The titanium plate-fin heat exchanger can be designed for pressures in excess of 200 bar and at temperatures up to 400^{o}C.

It is also possible to have exchangers with multi stream capability.

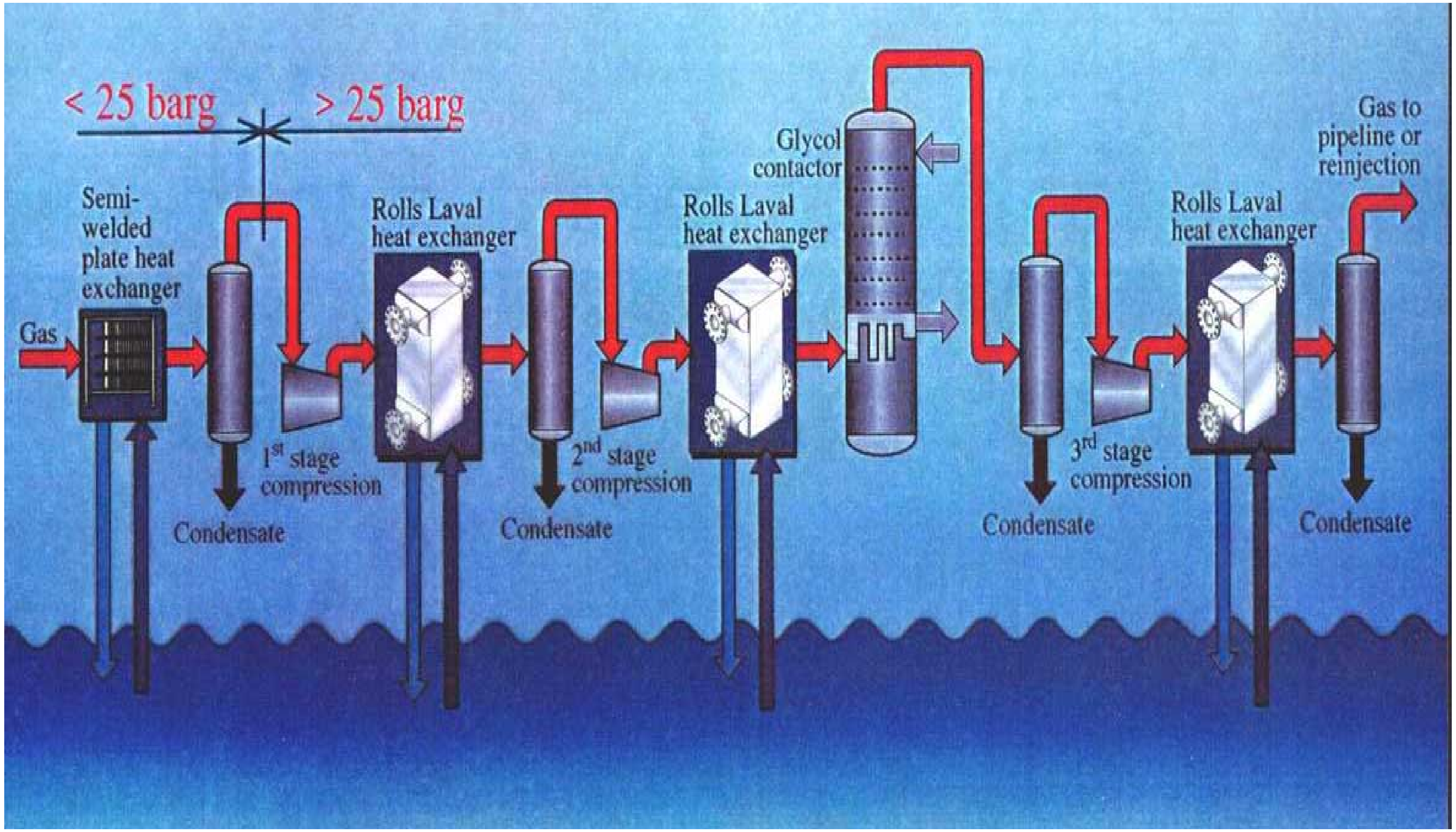
2.2.3.4 Principal Applications

The major application areas for the diffusion-bonded plate-fin heat exchanger are:

- Generic:
  - Gas-gas.
  - Gas-liquid.
  - Two-phase operations.

- Specific:
  - Gas compressor intercoolers.

The manufacturing method makes the unit ideal for duties where stream pressures in excess of 50 bar are likely to be encountered.



<u>Figure 2.2.9 – Example of Diffusion Bonded Exchanger in Operation</u>
<u>(Courtesy of Rolls-Laval Heat Exchangers Ltd)</u>

2.2.3.5 Comparison with Shell and Tube Heat Exchanger

An indication of the weight benefit associated with a titanium plate-fin heat exchanger compared to an equivalent shell and tube unit is given by the example below.

For a 250 bar duty, a shell and tube unit with titanium tubes and a titanium-clad shell would weigh 9.5 tonnes. The equivalent plate-fin heat exchanger would weigh 1 tonne.

A rule-of-thumb calculation suggests that, for a given duty, a shell and tube unit will be 5 to 10 times heavier.

The weight benefit is coupled with significant volume reductions.

Table 2.2.3 and Figure 2.2.10 illustrate an example gas cooler on a North Sea platform with a design pressure of 64 bar. It should be noted that for constrained space installations, the "space cost" may be substantially higher than the purchase cost of the heat exchanger.

Specification	Rolls Laval Plate-Fin Heat Exchanger	Shell and Tube Heat Exchanger
Material	Titanium	Titanium
Length, metres	1.1	10.0
Width, metres	1.0	1.3
Empty Weight, tonnes	3.7	18.0
Operating Weight, tonnes	4.0	28.0

Table 2.2.3 – Benefits of Compactness

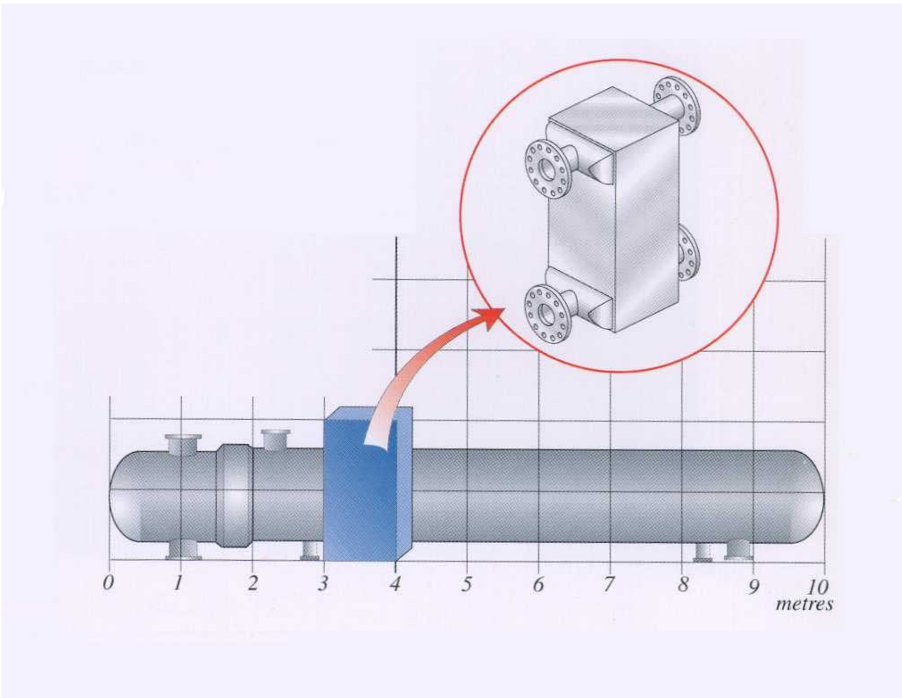


Figure 2.2.10 – Size difference for Gas Cooling Heat Exchanger on a North Sea Platform (Courtesy of Rolls Laval Heat Exchangers Ltd)

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.3

SPIRAL HEAT EXCHANGERS

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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SPIRAL HEAT EXCHANGERS

2.3.1 Introduction

Spiral heat exchanger design approaches the ideal in heat transfer equipment by obtaining identical flow characteristics for both media. The classic design of a spiral heat exchanger is simple; the basic spiral element is constructed of two metal strips rolled around a central core forming two concentric spiral channels. Normally these channels are alternately welded, ensuring that the hot and cold fluids cannot intermix.

The heat exchanger can be optimised for the process concerned by using different channel widths. Channel width is normally in the range 5 to 30 millimetres.

Plate width along the exchanger axis may be 2 m, as can the exchanger diameter, giving heat transfer areas up to 600 m^2.

Figure 2.3.1 – Spiral Heat Exchanger With End-Cap Removed (Giving Access to One Spiral Channel) (Courtesy of GEA Process Technology)

Gasketed flat covers are fitted to the open side of each channel resulting in easy access and reduced maintenance costs.

Spiral heat exchangers tend to be self-cleaning. The smooth and curved channels result in a lower fouling tendency with difficult fluids. Each fluid has only one channel and any localised fouling will result in a reduction in the channel cross sectional area causing a velocity increase to scour the fouling layer. This self-cleaning effect results in reduced operating costs particularly when the unit is horizontally mounted.

Horizontal mounting is essential when handling fibrous, high viscosity, particle-laden or clogging media since all particles potentially settle to the bottom of the channel curvature.

2.3.2 Construction

The spiral heat exchanger can be tailor-made to perform in a wide variety of duties in all metals that can be cold-formed and welded, such as carbon steel, stainless steel and titanium. High-grade alloys are routinely used for excellent resistance to corrosion and erosion.

In some cases double spacing may be used, produced by simultaneously winding four strips to form two channels for each fluid. These double channel systems are used when there is a large flowrate or small pressure drop, but should not be used for fouling media or media containing solids.

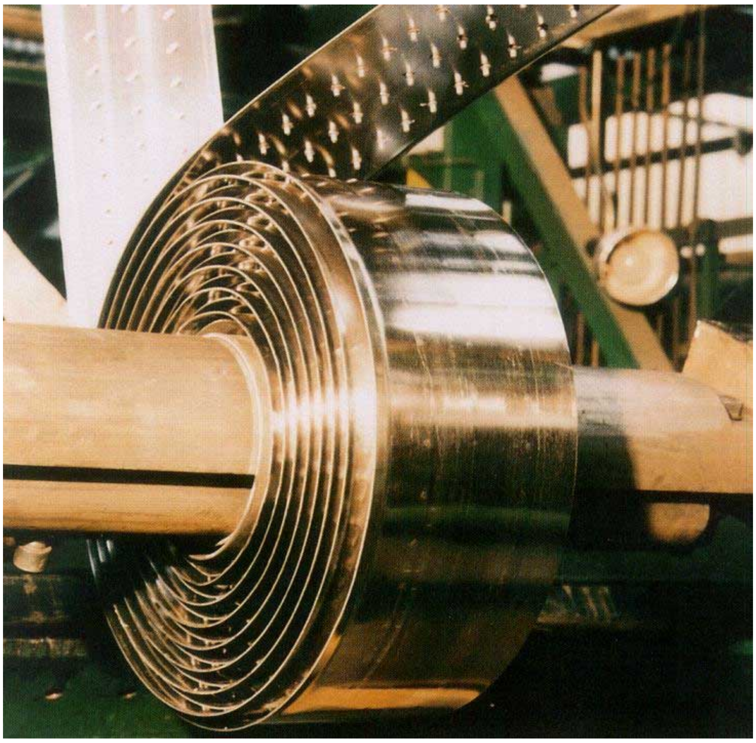

Figure 2.3.2 – Spiral Heat Exchanger Manufacture
(Courtesy of GEA Process Technology)

The use of spiral heat exchangers is not limited to liquid-liquid services. Variations to the basic design give exchangers that are suitable for liquid-vapour or liquid-gas services.

Typically spiral heat exchangers are available in three configurations:

- Type 1 – Media in full counter-current flow.

  The hot fluid enters at the centre of the unit and flows from the inside outward. The cold fluid enters at the periphery and flows towards the centre.

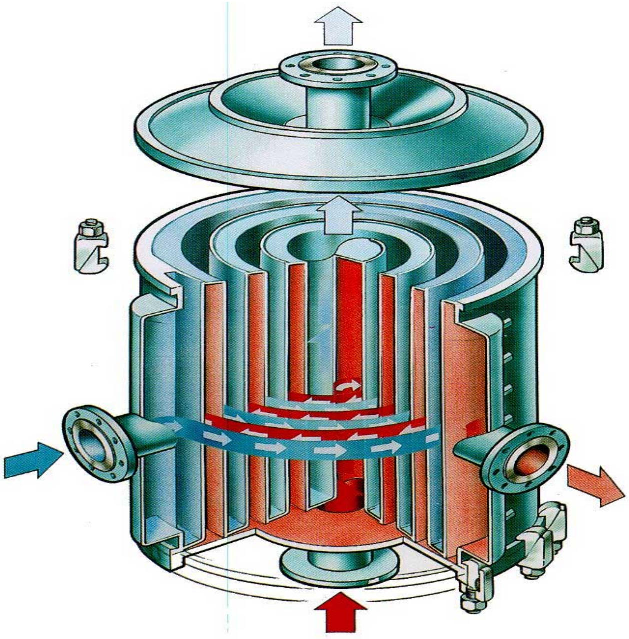

Figure 2.3.3 – Type 1 - Spiral Flow-Spiral Flow Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

- Type 2 – One medium in cross flow whilst the other is in spiral flow.

  The medium in crossflow passes through the open channels of the spiral usually in a vertical direction. The service fluid spiral flows through the other channel, welded shut, with side wall inlet and central outlet fed through the side wall as shown in Figure 2.3.4. This design can be used as either a condenser or vaporiser.

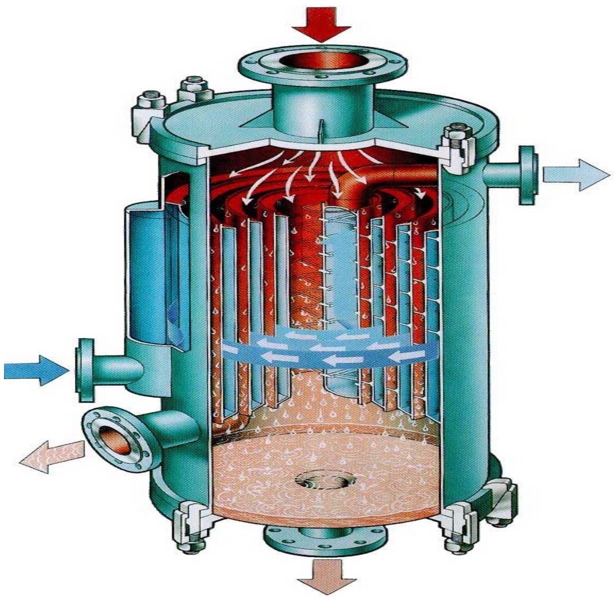

Figure 2.3.4 – Type 2 - Cross Flow-Spiral Flow Heat Exchanger
(Courtesy of Alfa Laval Thermal Division)

- Type 3 – Combination design.

  A gas or vapour mixture to liquid exchanger combines the above two designs; the hot stream enters at the top and flows tangentially through the exchanger exiting at the side.

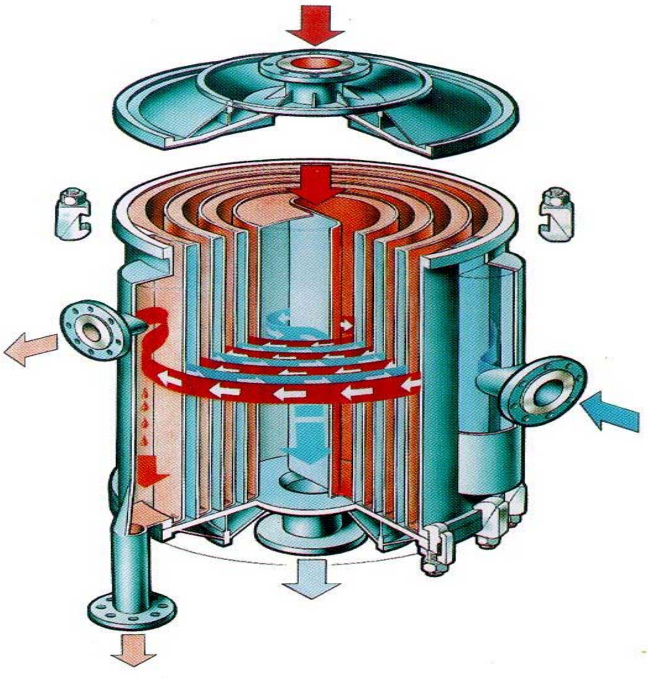

Figure 2.3.5 – Type 3 - Combination Cross-Flow and Spiral Flow-Spiral Flow
(Courtesy of Alfa Laval Thermal Division)

2.3.3 Operating Limits

Typically, the maximum design temperature is 400^{o}C set by the limits of the gasket material. Special designs without gaskets can operate with temperatures up to 850^{o}C. Maximum design pressure is usually 15 bar, with pressures up to 30 bar attainable with special designs.

2.3.4 Principal Applications

The design is ideal for fluids prone to fouling, or polluted with particles as a result of the relatively large channel width. Hence, it is ideal for use in the food industry (sauces, slush and slurry) as well as in brewing and wine making.

Spiral heat exchangers have many applications in the chemical industry including $TiCl_4$ cooling, PVC slurry duties, oleum processing and heat recovery from many industrial effluents.

Spiral heat exchangers also provide temperature control of sewage sludge digesters plus other public and industrial waste plants.

Spiral heat exchangers have perfect counter-current flow paths that permit the best possible overlap of exit temperatures. As such, they can maximise the heat recovery on large-scale cogeneration projects although they may be more expensive than plate designs.

Spiral exchangers can be mounted directly onto the head of distillation columns acting in a condensing or reflux role. Specific advantages are ease of installation, low pressure drop and large flow cross-section. Consequently, there are many condensing applications in all process industries particularly for condensing under vacuum.

2.3.5 Comparison with Shell and Tube Heat Exchanger

Spiral designs have a number of advantages compared to shell and tube heat exchangers:

- Optimum flow conditions on both sides of the exchanger.
- An even velocity distribution, with no dead-spots.
- An even temperature distribution, with no hot or cold-spots.
- More thermally efficient with higher heat transfer coefficients.
- Copes with exit temperature overlap, or crossover, whereas shell and tube units require multi-shells in series to handle temperature crossover.
- Small hold up times and volumes.
- Removal of one cover exposes the total surface area of one channel providing easy inspection cleaning and maintenance.

For the same duty, a spiral heat exchanger heat transfer area would be 90m^2 compared to 60m^2 for a plate and frame design or 125m^2 for a shell and tube design. The physical size comparison is shown in Figure 2.3.6

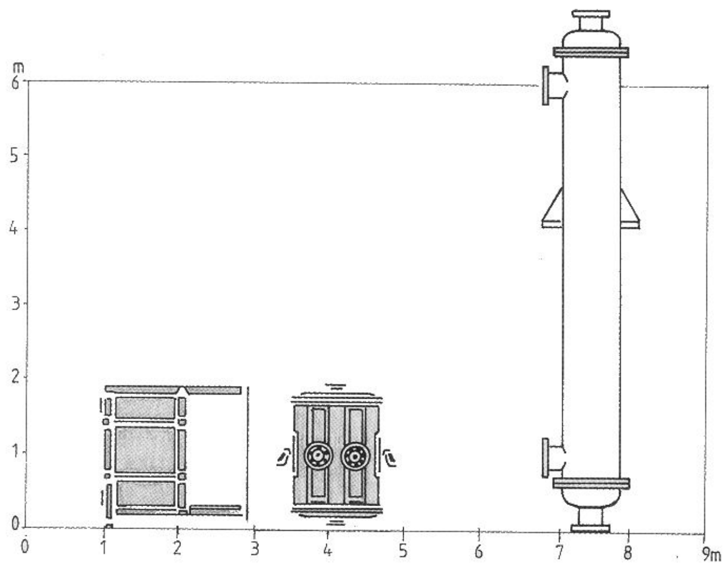

Figure 2.3.6 – Heat Exchanger Size Comparison for Plate, Spiral, and Shell and Tube Heat Exchangers (Courtesy of GEA Process Technology)

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.4

PRINTED CIRCUIT HEAT EXCHANGERS

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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PRINTED CIRCUIT HEAT EXCHANGERS

2.4.1 Introduction

Printed circuit heat exchangers are highly compact, corrosion resistant heat exchangers capable of operating at pressures of several hundred atmospheres and temperatures ranging from cryogenic to several hundred degrees Celsius.

The printed circuit heat exchanger design offers a unique combination of innovative manufacturing technology and potential breadth of application. In common with some other compact heat exchangers, it is potentially more than just a compact plate heat exchanger; the structure has applications in a variety of other unit operations, including reactors, mass transfer and mixers.

Printed circuit heat exchangers are constructed from flat alloy plates with fluid flow passages photo-chemically machined (etched) into them. This process is similar to manufacturing electronic printed circuit boards, and gives rise to the name of the exchangers. An example of a plate showing a 'herringbone' pattern of flow paths is shown in Figure 2.4.1.

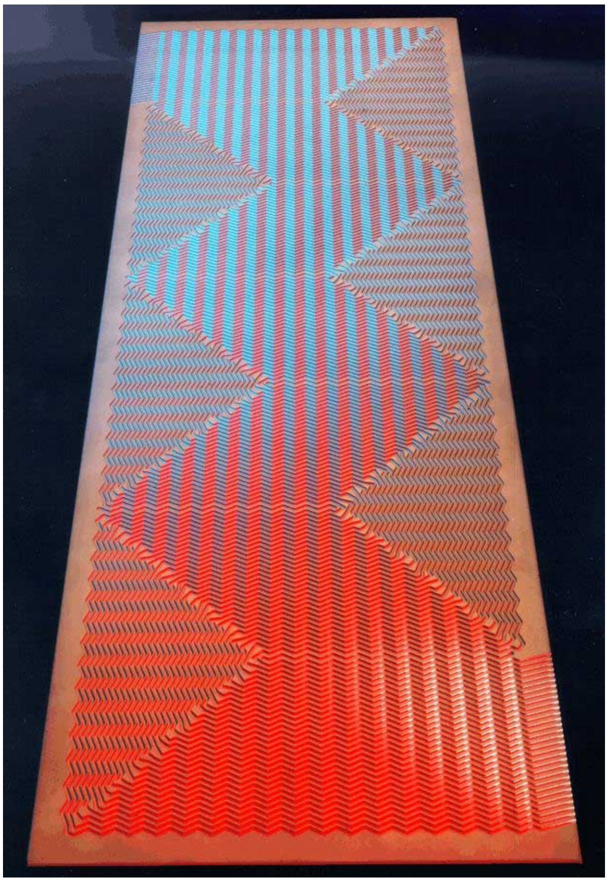

Figure 2.4.1 – Fluid Flow Paths on a Typical Printed Circuit Heat Exchanger Etched Plate (Courtesy of Heatric Ltd)

Heatric originally developed printed circuit heat exchangers in Australia, where this type of heat exchanger first became commercially available for refrigeration and process applications in 1985. In 1990, Heatric moved to the UK and has supplied printed circuit exchangers into the offshore and process sectors, both in the UK and overseas.

2.4.2 Construction

The standard manufacturing process involves chemically milling (etching) the fluid flow passages into the plates. This allows enormous flexibility in thermal/hydraulic design, as complex new plate patterns require only minimal re-tooling costs.

This plate/channel forming technique can produce a wide range of flow path sizes, the channels varying typically from 0.5 to 2.0 mm in depth.

Stacks of etched plates, carrying flow passage designs tailored for each fluid, are diffusion bonded together to form a compact, strong, all-metal heat exchanger core. A cross-section through a typical core sample is shown in Figure 2.4.2. No gaskets or brazing materials are required for the assembly. Diffusion bonding allows the plates to be joined so that the bond acquires the same strength as the parent metal. The thermal capacity of the exchanger is built to the required level by welding together diffusion bonded blocks to form the complete heat exchanger core. Finally, fluid headers and nozzles are welded to the cores, in order to direct the fluids to the appropriate sets of passages. Figure 2.4.3 shows a completed heat exchanger unit.

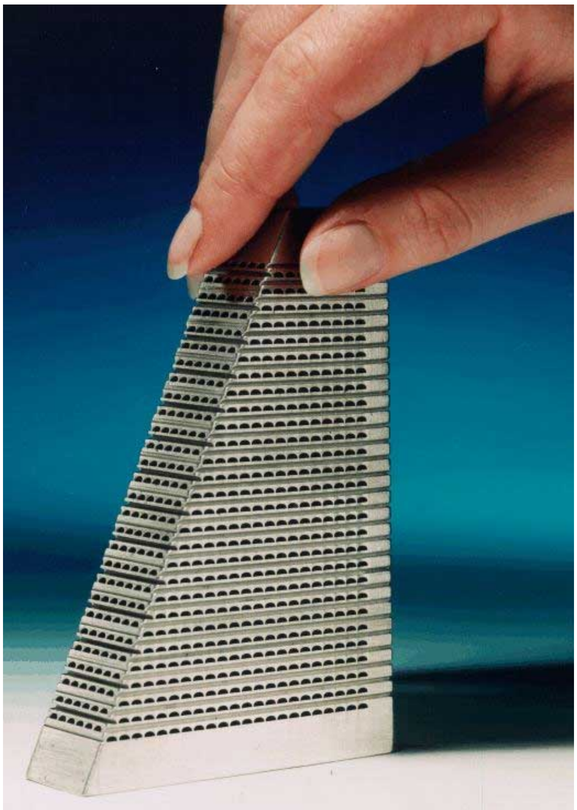

Figure 2.4.2 – Cross-section Through a Typical Printed Circuit Heat Exchanger Core (Courtesy of Heatric Ltd)

Figure 2.4.3 – Gas Dew Point Control Printed Circuit Heat Exchanger
(Courtesy of Heatric Ltd)

Materials of construction include stainless steel (SS 300 series) and titanium as standard, with nickel and nickel alloys also being commonly used. A copper variant is being developed.

2.4.3 Operating Limits

Mechanical design is flexible; etching patterns can be adjusted to provide high pressure containment where required. Due to its construction, the printed circuit heat exchanger is able to withstand substantial pressures. Pressures as high as 200 bar are routine, with values in the range 300 - 500 bar being possible.

The all welded construction is compatible with very high temperature operation, and the use of austenitic steel allows cryogenic operation. Operating temperature ranges from -200^{o}C to +900^{o}C, the upper limits depending on the metal selected and the pressure duty.

Passages are typically of the order of 2 mm semi-circular cross-section (i.e. 2 mm across and 1 mm deep) for reasonably clean applications, although there is no absolute limit on passage size.

Prime heat transfer surface densities, expressed in terms of effective heat transfer area per unit volume, can be up to 2500 m^2/m^3. This is higher than prime surface densities in gasketed plate exchangers, and an order of magnitude higher than normal prime surface densities in shell and tube exchangers.

2.4.4 Operation

Printed circuit heat exchangers are all welded so there is no braze material employed in construction, and no gaskets are required. Hence the potential for leakage and fluid compatibility difficulties are reduced and the high level of constructional integrity renders the designs exceptionally well suited to critical high pressure applications, such as gas compression cooling exchangers on offshore platforms.

The thermal design of printed circuit heat exchangers is subject to very few constraints. Fluids may be liquid, gas or two-phase, multi-stream and multi-pass configurations can be assembled and flow arrangements can be truly counter-current, co-current or cross-flow, or a combination of these, at any required pressure drop.

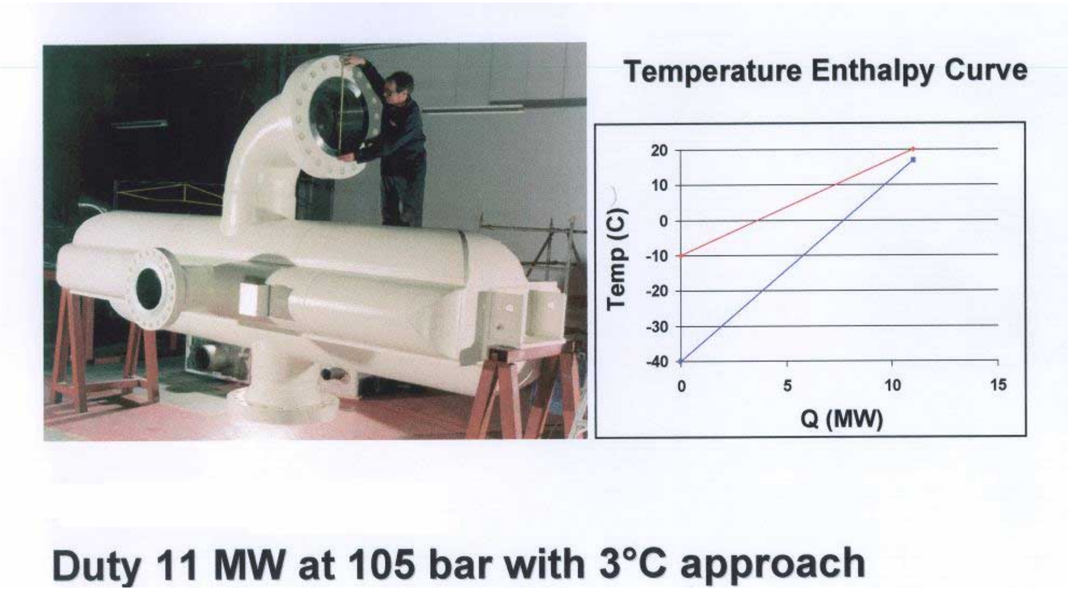

Figure 2.4.4 - Application Showing Close Temperature Approach
(Courtesy of Heatric Ltd)

Where required high heat exchange effectiveness (over 98%) can be achieved through very close temperature approaches in counter-flow. To simplify control, or to further maximise energy efficiency, more than two fluids can exchange heat in a single core. Heat loads can vary from a few watts to many megawatts, in exchangers weighing from a few kilograms to thousands of kilograms.

Flow induced vibration, an important source of failure in shell and tube exchangers, is absent from printed circuit heat exchangers.

A simple strainer upstream of the unit will remove outsize particles, while the corrosion resistant materials of construction for printed circuit heat exchangers, the high wall shear stresses, and the absence of dead spots assist in resisting fouling deposition.

2.4.5 Design

Detailed thermal design of printed circuit heat exchangers is supported by proprietary design software developed by the manufacturer that allows infinite geometric variation to passage arrangements during design optimisation. Variations to passage geometry have negligible production cost impact since the only tooling required for each variation is a photographic transparency for the photo-chemical machining process.

Although the scope of printed circuit heat exchanger capabilities is much wider, as a sizing guide it is safe to assume that channel patterns can be developed to mimic any j- and f- factor characteristics (found in publications such as "Compact Heat Exchangers" by Kays and London) for aluminium surfaces, or data presented by gasketed plate manufacturers.

It is rarely necessary to apply a correction factor substantially less than 1 to the LMTD calculated for an heat exchange, no matter how high the effectiveness required, because of the printed circuit heat exchanger counter-flow capabilities. Pressure drops can be specified at will, however as with all heat exchangers, lower allowable pressure drops will result in lower heat transfer coefficients and hence larger exchangers.

2.4.6 Principal Applications

Printed circuit heat exchangers extend the benefits of compact heat exchangers into applications where pressure, temperature or corrosion prevents the use of conventional plate exchangers.

As mentioned above, the printed circuit heat exchanger can handle gases, liquids and two-phase flows. The manufacturer cites four main application areas, as listed below:

- Fuels processing:
    - Gas processing e.g. compressor cooling, liquids recovery.
    - Dehydration.
    - Synthetic fuels production e.g. methanol.
    - Reactor feed/effluent exchange.

- Chemical processing:
    - Acids e.g. nitric, phosphoric.
    - Alkalis e.g. caustic soda, caustic potash.
    - Fertilisers e.g. ammonia, urea.
    - Petrochemicals e.g. ethylene, ethylene oxide, propylene.
    - Pharmaceuticals.
    - Plastics e.g. formaldehyde, phenol.

- Power and energy:
    - Feedwater heating.
    - Geothermal generation.
    - Chemical heat pumps.

- Refrigeration:
  - Chillers and condensers.
  - Cascade condensers.
  - Absorption cycles.

Figure 2.4.5 - Typical Compression Cooling Printed Circuit Heat Exchanger (Courtesy of Heatric Ltd)

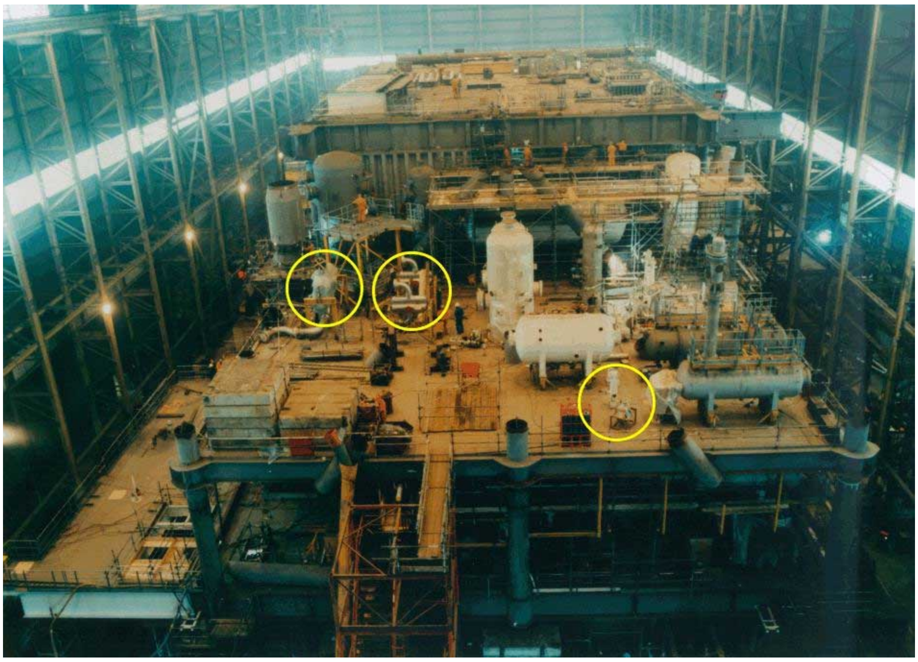

Figure 2.4.6 – Compression Cooling Printed Circuit Heat Exchangers Installed on a Gas Platform (Courtesy of Heatric Ltd)

The printed circuit heat exchanger pictured in Figure 2.4.7 is a multi-stream unit. Such a unit cools high pressure feed gas with a combination of cold separator gas, cold separator liquid and refrigerated triethylene glycol (TEG) solution.

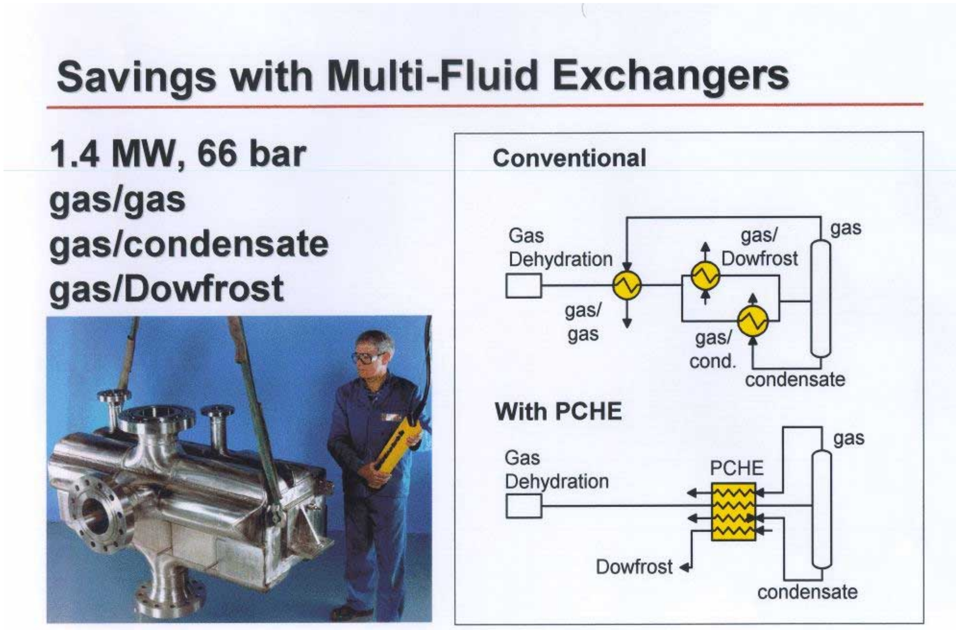

Figure 2.4.7 – Multi-stream Printed Circuit Heat Exchanger Replacing Three Shell and Tube Units (Courtesy of Heatric Ltd)

2.4.7 Comparison with Shell and Tube Heat Exchanger

Figure 2.4.8 illustrates the size difference between a comparable printed circuit heat exchanger and stack of three series shell and tube units used for gas dew point control. The duty is 2,350 kW across a 4°C LMTD.

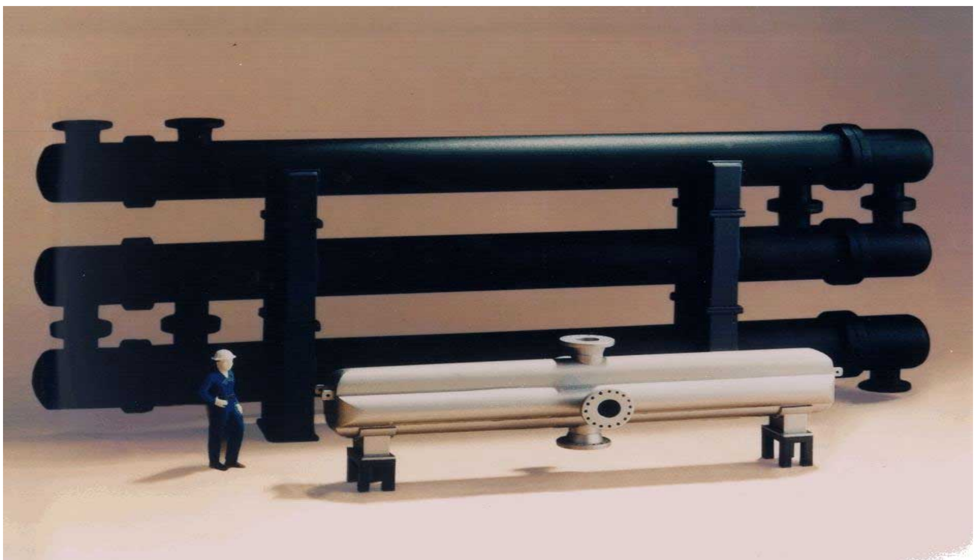

Figure 2.4.8 – Comparison of Printed Circuit Heat Exchanger and Shell and Tube Heat Exchangers of Equivalent Capacity (Courtesy of Heatric Ltd)

The printed circuit heat exchanger illustrated in Figure 2.4.8 has 600 m^2 of surface and a design pressure of 124 bar. Its weight is 15 tonnes, compared to 105 tonnes for equivalent shell and tube heat exchangers.

Printed circuit heat exchanger cores are typically 5 to 10 times smaller than shell and tube exchangers tube bundles of equivalent performance.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.5

PLATE AND SHELL HEAT EXCHANGERS

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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2.5.2 Construction
2.5.3 Operating Limits
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2.5.5 Comparison with Shell and Tube Heat Exchanger

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2.5.1 General Arrangement of a Plate and Shell Exchanger
2.5.2 Closed Plate and Shell Exchanger

PLATE AND SHELL HEAT EXCHANGERS

2.5.1 Introduction

The plate and shell heat exchanger combines the merits of shell and tube with plate heat exchangers, while externally resembling the former in some respects.

Plate and shell heat exchangers feature an outer shell enclosing circular plates welded into pairs. The cooling medium flows on the shell side between the pairs of plates. As a plate is more thermally efficient than a tube, this achieves a significantly higher level of heat transfer.

2.5.2 Construction

The construction of a plate and shell heat exchanger involves welding together, in pairs, circular plates of a similar surface form and material to those of plate and frame heat exchangers. The plates are then located inside a shell, as shown in Figure 2.5.1.

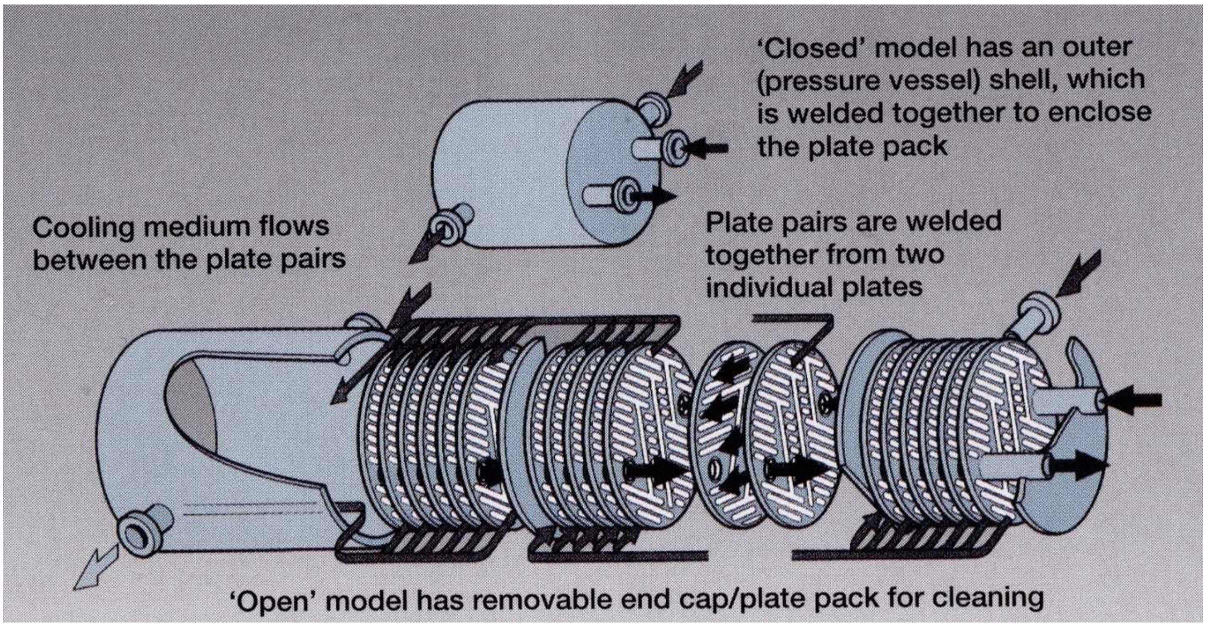

Figure 2.5.1 – General Arrangement of a Plate and Shell Heat Exchanger (Courtesy of APV)

A 'closed' model has a welded shell or an 'open' model has a removable end flange to facilitate shell-side cleaning.

Generally the hot fluid is passed through the plate side, while the cooling fluid is directed on the shell side. The shell side fluid is routed through individual passes via a baffle plate similar to the shell in the tubular type heat exchanger. Multi-pass arrangements are possible, flow directors on both the shell and plate side adjust the flow paths.

Figure 2.5.2 – Closed Plate and Shell Heat Exchangers
(Courtesy of APV)

Current plate and shell heat exchanger models accommodate up to 600 plates in a shell 2.5 m long with a 1 m diameter. Plate and shell heat exchangers are available with a heat transfer surface area of up to 500m^2.

Standard plate materials are Titanium B265, Avesta 254 SMO and AISI 316. The shell can be made of St 35.8 or AISI 316 or other materials, such as Hastelloy or nickel, if necessary.

2.5.3 Operating Limits

The maximum operating temperature of a plate and shell heat exchanger is 900^{o}C, and maximum working pressure is 100 bar. Single units, which can be operated in parallel for higher throughputs, can currently handle flow rates of 11 litres per second on the shell side.

2.5.4 Principal Applications

Plate and shell heat exchangers can work with aggressive media and acids, which cannot be handled by conventional gasketed plate heat exchangers. They can also withstand extreme temperature shocks and pressure shocks due to their rigid and compact construction.

The principal applications for plate and shell heat exchangers are:

- Heating including district heating.
- Cooling including cryogenic applications.
- Heat recovery.
- Combined exchanger/reactors vessels.
- Condensation/evaporation.

A variety of fluids can be handled including:

- Water.
- Thermal oil.
- Solvents.
- Steam.
- Hydrocarbons and organic chemicals.
- Refrigerants.

2.5.5 Comparison with Shell and Tube Heat Exchanger

Data that directly compares the shell and plate unit with a shell and tube heat exchanger are not available, but shell and plate heat exchangers have been compared with brazed plate heat exchangers. Like brazed plate heat exchangers, plate and shell heat exchangers reach very close approach temperatures. Furthermore due to the flexible layout of flow path configurations, overlapping or crossover of exit temperature is possible.

For heat exchangers of equivalent area and capacity, plate and shell designs are smaller due to the higher ratio of heat transfer area and specific volume. It is claimed that the plate and shell heat exchanger will occupy only 20 to 30% of the footprint of equivalent capacity shell and tube types. The maximum operating pressure of the plate and shell unit will also be higher.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 2.6

POLYMER HEAT EXCHANGERS

This technology module contains a brief introductory description to the exchanger type above, followed by information on construction, construction materials, operating limits and principal applications. Where appropriate, a comparison is made with conventional shell and tube heat exchangers to emphasise size and weight reductions that can be achieved by using compact heat exchangers.

The Module 3 series present further information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency. heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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2.6.1 TEFLON Shell and Tube Heat Exchanger
2.6.2 TEFLON Heating Coil

POLYMER HEAT EXCHANGERS

2.6.1 Introduction

While most of the heat exchangers used in the process industries are metallic, other materials are available. Carbon, for example, is used for sulphuric acid, TEFLON and glass are occasionally used where extensive corrosion may occur. Ceramic units are available for use at high temperatures.

Polymer heat exchangers are available for heating, ventilating and air conditioning duties. The application of polymers in process heat exchangers, often stimulated by the need to protect against corrosion, can have other benefits that extend into the area of compact heat exchangers.

2.6.2 TEFLON Heat Exchangers

2.6.2.1 Construction

Heat exchangers incorporating TEFLON were first introduced for corrosive or abrasive applications in chemical plants.

As plastics have a relatively low thermal conductivity, small-bore tubes with thin wall sections were used. Typically 2.5 mm o/d tubes were used with a wall thickness of 10% of the outside diameter.

TEFLON heat exchangers are available as shell and tube designs, or as immersion coils.

TEFLON "Q" is a resin development that increases the temperature capability up to 200^{o}C and has approximately twice the thermal conductivity of normal TEFLON. In addition, this resin is tougher and more abrasion resistant.

Tube diameters have been introduced from 2.5 to 9.5 mm to increase flexibility.

2.6.2.2 Shell and Tube Units

Polymer shell and tube units tend to be single pass, counter-current designs incorporating flexible tubes of TEFLON FEP or TEFLON "Q" fused at both ends to form a honeycomb structure. Shell-side baffles promote cross-flow and optimise thermal efficiency. All surfaces exposed to the process stream are made of TEFLON to resist fouling and corrosion.

The small bore tubes produce a large surface area for a given volume; for example 1000 tubes of 4.45 mm o/d inside a 10 inch shell gives a heat transfer area of 275 m^2/m^3.

Usually the shell is carbon steel although other shell materials are available. In the case of heat exchange between two corrosive streams, the shell can be TEFLON lined. Shell diameters range from 76 to 355 mm in lengths from 0.6 to 7.3 m.

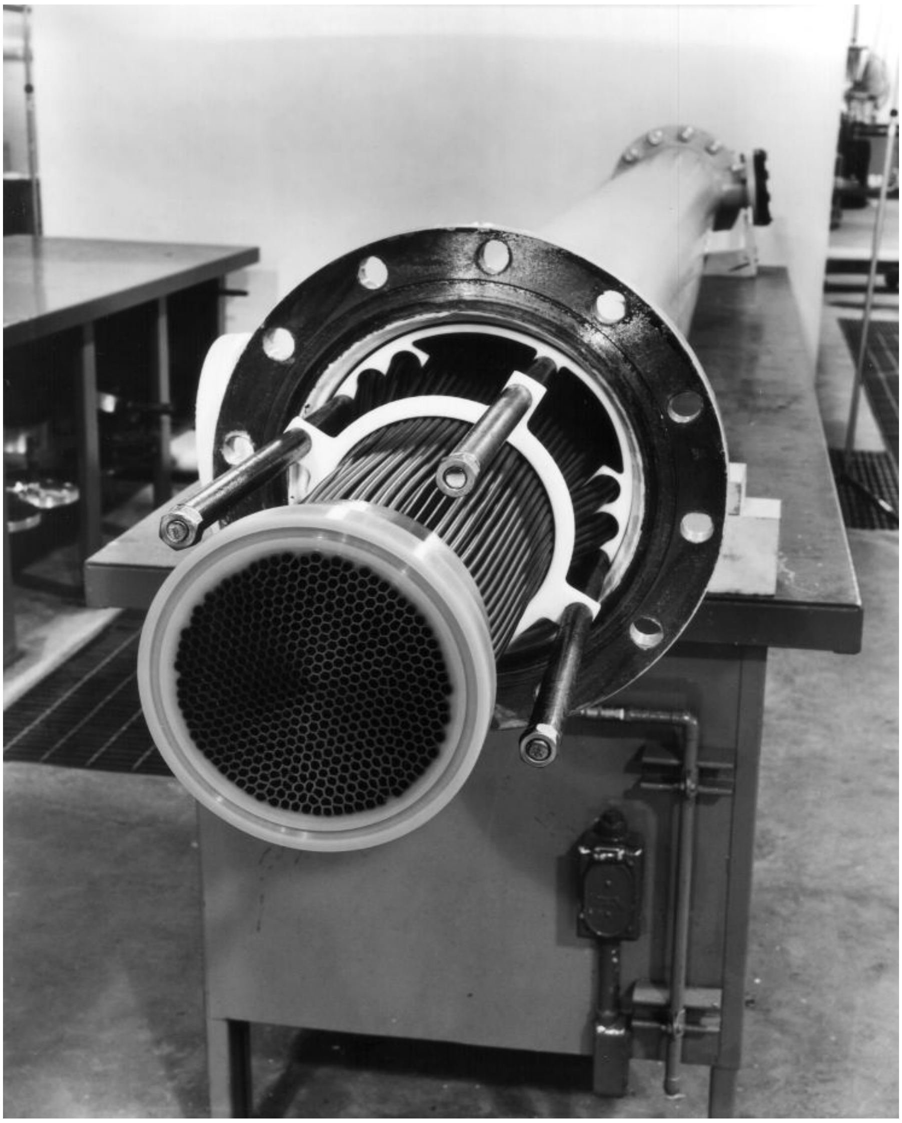

Figure 2.6.1 – TEFLON Shell and Tube Heat Exchanger
(Courtesy of Ametek)

2.6.2.3 Immersion Coils

Slimline coils are used in medium and large process tanks for heating or cooling purposes. Typically 300 tubes of 3 mm diameter give 166 m^2/m^3.

Units are available in lengths from 1.22 to 4.9 m with surface areas from 3.2 to 23.7 m^2.

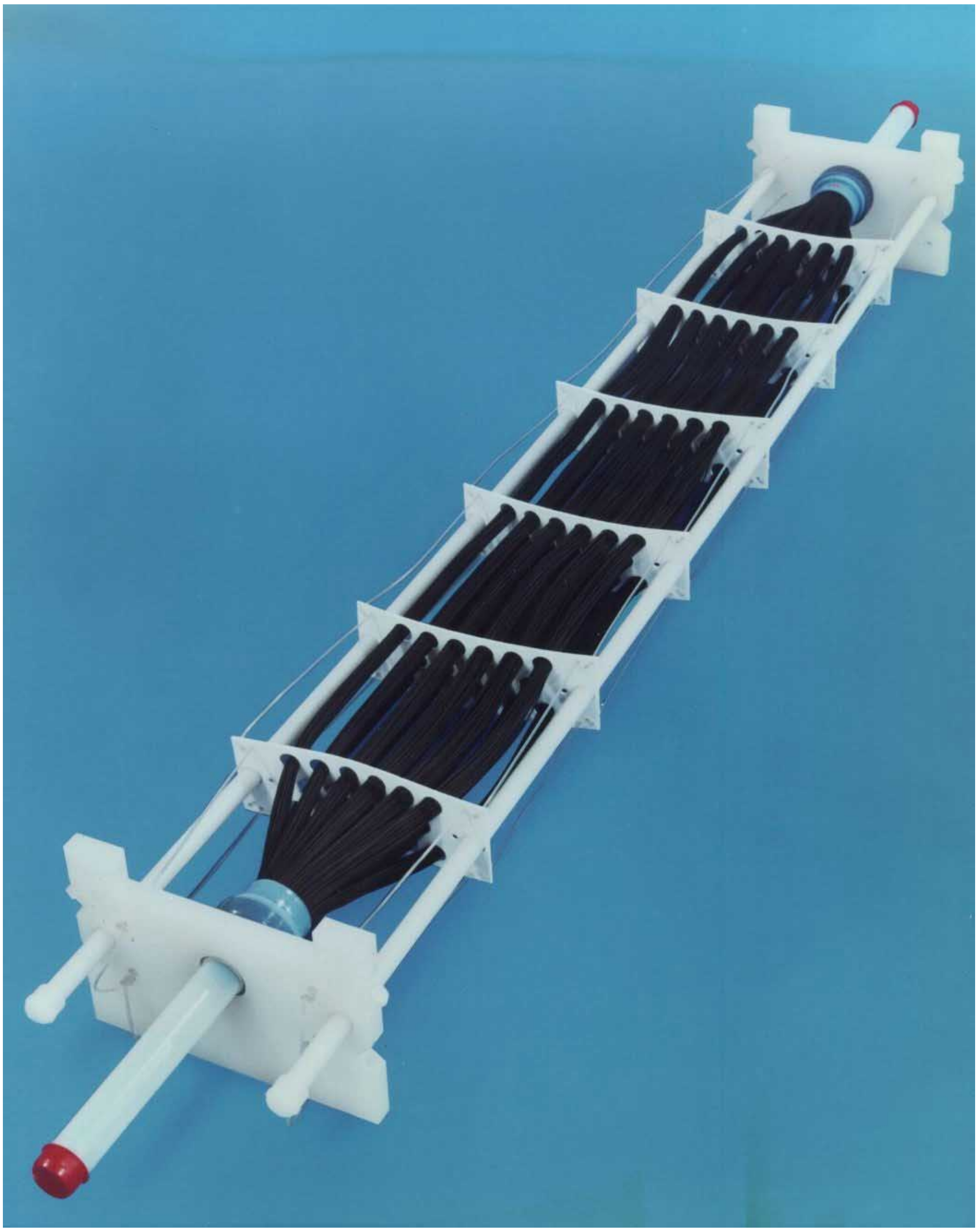

Figure 2.6.2 – TEFLON Heating Coil
(Courtesy of Ametek)

2.6.2.4 Operating Limits
Process stream temperatures are restricted to less than 200^{o}C

2.6.2.5 Applications
These specialist exchangers are used for corrosive process streams, such as hydrochloric acid, or for abrasive process streams.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.0

COMMON ASPECT MODULES

This module series presents further information common to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling and how to minimise it, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

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3.1 Advantages and Limitations
3.2 Fouling
3.3 Applications
3.4 Energy Efficiency and Heat Exchange
3.5 Heat Transfer Enhancement
3.6 Selection, Specification and Operation
3.7 Process Intensification
3.8 Software

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.1

ADVANTAGES AND LIMITATIONS

This module presents the generic process advantages and limitations of compact heat exchanger designs. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of heat exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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- 3.1.2.1 Improved Heat Exchanger Thermal Effectiveness
- 3.1.2.2 Closer Approach Temperatures
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ADVANTAGES AND LIMITATIONS OF COMPACT HEAT EXCHANGERS

3.1.1 Introduction

Final selection of heat exchanger designs unique for each duty. In appropriate applications, compact designs offer substantial advantages over more conventional exchanger designs, usually shell and tube exchangers.

Of course, the benefits of using compact heat exchanger designs are only realised in appropriate applications. Equipment suppliers should always be consulted for specialist information on the suitability of their compact designs. However, section 3.1.2 describes the generic advantages of using compact designs and section 3.1.3 indicates how limitations may be overcome.

The requirement in most heat transfer applications is to maximise the amount of heat transferred, subject to capital cost and pressure drop constraints. Both cost and heat transfer performance generally increase in proportion to exchange surface area.

3.1.2 Generic Advantages of Compact Designs

The main benefits of using compact heat exchangers are:

- Improved heat exchanger thermal effectiveness.
- Closer approach temperatures.
- High heat transfer coefficients and transfer areas per exchanger volume.
- Smaller size.
- Multi-stream and multi-pass configurations.
- Tighter temperature control.
- Energy savings.
- Reduced inventory volume and hazard risk.
- Process intensification using combined reactor/exchangers.

These technological advantages can be converted into reduced operational and capital costs, and conserve energy, compared to shell and tube units. The performance characteristics of compact heat exchangers have particular relevance in process integration; for example in composite process heating and cooling curves.

The following sections elaborate these aspects.

3.1.2.1 Improved Heat Exchanger Thermal Effectiveness (E)

A major advantage of most compact designs is their greater efficiency or thermal effectiveness (E). The effectiveness of a heat exchanger can simply be expressed as the ratio of the actual heat transfer to the maximum possible heat transfer. The effectiveness is a function of the heat capacity of the fluid streams, the overall heat transfer coefficient and the area of heat transfer surface.

The benefits of improved heat exchanger efficiencies are described below. One advantage of a higher effectiveness - a closer approach temperature difference - is a beneficial effect on the relative position of the hot and cold composite curves utilised in a process integration analysis. This can lead to significant energy cost savings in process heating and cooling duties.

Heat transfer performance can be measured by assessing the efficiency or, more strictly, the 'effectiveness' of heat exchangers. Consider the case of two counter-current streams as depicted in Figure 3.1.1.

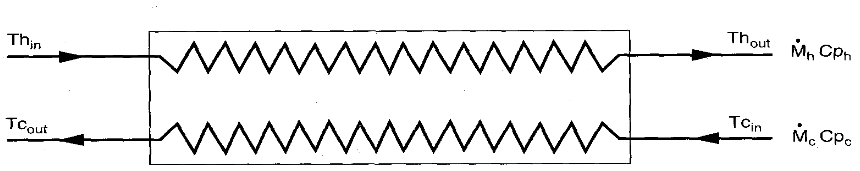

Figure 3.1.1 – Idealised Conditions for Two Counter-current Streams in a Heat Exchanger

The theoretical maximum amount of heat that can be transferred in this simple configuration is given by:

$$\dot{Q}_{max} = (\dot{M}Cp)_{min}(T_{h,in} - T_{c,out}) \quad (1)$$

where
$$(\dot{M}Cp)_{min} = \dot{M}_h Cp_h \quad \text{if} \quad \dot{M}_h Cp_h < \dot{M}_c Cp_c$$

$$(\dot{M}Cp)_{min} = \dot{M}_c Cp_c \quad \text{if} \quad \dot{M}_h Cp_h > \dot{M}_c Cp_c$$

The effectiveness is a measure of heat transfer performance. The thermal effectiveness (E) may be defined as:

$$E = \dot{Q}_{act}/\dot{Q}_{max} \quad (2)$$

where $\dot{Q}_{act}$ = actual amount of heat transferred

$\dot{Q}_{max}$ = theoretical maximum heat transfer

The actual amount of heat transferred ($\dot{Q}_{act}$), is given by:

$$\dot{Q}_{act} = \dot{M}_h Cp_h (T_{h,in} - T_{h,out}) \quad (3)$$
$$\dot{Q}_{act} = \dot{M}_c Cp_c (T_{c,out} - T_{c,in})$$

Therefore E is given by the equation:

$$E = \frac{\dot{M}_h Cp_h (T_{h,in} - T_{h,out})}{(\dot{M}Cp)_{min}(T_{h,in} - T_{c,in})} \quad (4)$$

$$E = \frac{\dot{M}_c Cp_c (T_{c,out} - T_{c,in})}{(\dot{M}Cp)_{min}(T_{h,in} - T_{c,in})}$$

If $\dot{M}_h Cp_h = \dot{M}_c Cp_c$, then

$$E = \frac{(T_{h,in} - T_{h,out})}{(T_{h,in} - T_{c,in})} \quad (5)$$

$$E = \frac{(T_{c,out} - T_{c,in})}{(T_{h,in} - T_{c,in})}$$

For shell and tube heat exchangers, the thermal effectiveness (E) is typically 0.75. Values in excess of 0.95 are economically possible with compact heat exchangers.

3.l.2.2 Closer Approach Temperatures

Approach temperature is an alternative measure of heat exchanger performance. Equation (6) shows that as the outlet temperature of the cold stream $(T_{c,out})$ approaches the inlet temperature of the hot stream $(T_{h,in})$, the thermal effectiveness (E) increases.

A shell and tube heat exchanger with an effectiveness of 0.75, heating a single phase fluid from 10°C with a hot source stream at l00°C, will give a cold stream outlet temperature of 77.5°C: that is, an approach temperature of 22.5°C.

A compact heat exchanger with an effectiveness of 0.95, used for the same application, would give a cold stream outlet temperature of 95.5°C: that is, an approach temperature of only 4.5°C.

$$\Delta T_{min} = (1 - E)(T_{h,in} - T_{c,in}) \quad (6)$$

3.1.2.3 Heat Transfer Coefficient and Area

Heat transfer can be predicted by the equation:

$$\dot{Q} = UA\Delta T \quad (7)$$

where $\dot{Q}$ = heat transfer rate, W/m^2
U = overall heat transfer coefficient, W/m^2/K
A = heat transfer surface area, m^2
ΔT = temperature difference between the streams, K or °C

Increasing U and/or A will increase the heat transfer rate for given temperature conditions and will, therefore, improve effectiveness.

Compact heat exchangers have:

- High heat transfer coefficients due to the small hydraulic diameter of the flow passages.
- High heat transfer surface areas for a given volume of heat exchanger. Typically, compact exchanger area/volume ratios may be up to an order of magnitude greater than those of shell and tube exchangers depending on the exchanger type.

Furthermore, the high heat transfer coefficient is frequently achieved without excessive pressure drop.

An arrangement of shell and tube heat exchangers in series could provide high heat transfer areas and the effectiveness of such an assembly could thus be made as high as required. However, the greater area/volume ratio and high heat transfer coefficients of compact heat exchangers give a high effectiveness with a much smaller overall volume. A cost-effective heat exchanger with a high effectiveness can therefore be achieved with a compact design.

3.1.2.4 Implications for Process Integration

The capabilities of compact heat exchangers described in Section 3.1.2. are particularly important in process integration. This is because they allow a significant reduction in the 'pinch-point' temperature.

The implications of this statement can be explained by reference to Figure 3.1.2 which shows composite curves produced from a number of hot and cold streams.

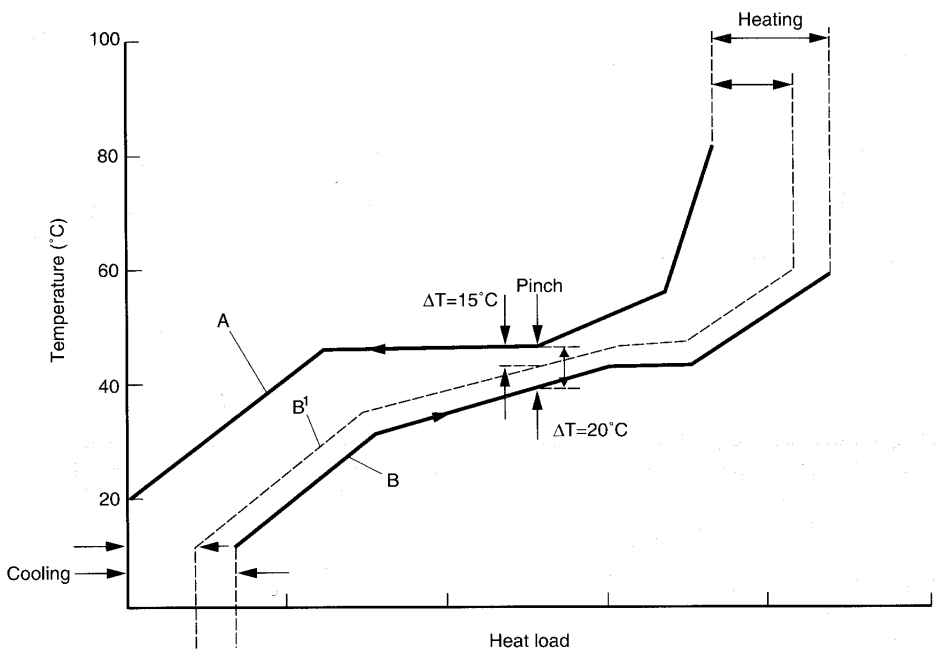

Figure 3.1.2 – Effect of Approach Temperature on Location of Composite Curves and 'Pinch-Point'

Curve A is a composite stream made up of four individual hot streams (streams that are being cooled), while curve B is a similar representation of four cold streams (streams that are being heated). The minimum approach temperature, which is determined by the conventional heat exchangers employed, means that the allowable temperature difference between the two composite streams at the pinch point has been set at 20°C. It is clear from the position of curves A and B that the hot stream requires additional cooling in order to reach its desired temperature level, while stream B requires external heat input.

By using more effective heat exchangers, it is possible to reduce the temperature difference at the pinch. In this example, it is conservatively assumed that it can be reduced by 5°C to 15°C. The effect of this is two-fold. As the curves come closer together, the amount of cooling that the hot stream needs in order to reach its desired temperature is reduced by the amount shown horizontally on the graph. The amount of heat needed by the cold stream is also decreased. These reductions are directly reflected in the energy input required. The energy efficiency of the overall process is therefore improved.

Effective heat exchangers are an essential element of realising the benefits of recovering waste heat from process streams in integrated systems.

3.1.2.5 Smaller Size

Another advantage of compact heat exchangers is their smaller physical characteristics for a given heat transfer duty compared to most shell and tube heat exchangers.

This has benefits that extend well beyond the heat exchanger itself, including, for example, reduced support structure and more convenient location (particularly when installed on a 'greenfield' site). Obviously in restricted space applications, reduced size and weight are important selection criteria. Also, the additional space needed to remove the tube bundle from the shell of a shell and tube unit should not be overlooked; the equivalent space required on a compact heat exchanger with a removable core is proportionally less.

Compact heat exchangers, particularly when their total installed cost is considered, tend to be significantly cheaper than their conventional counterparts. While this may not always be the case when low-cost metals can be used, the benefits of compact heat exchangers are much more apparent when the heat exchanger has to be made from an expensive material such as nickel or titanium. Here the cost per kilogram of raw material dominates the cost of the exchanger, and often adjacent ancillaries.

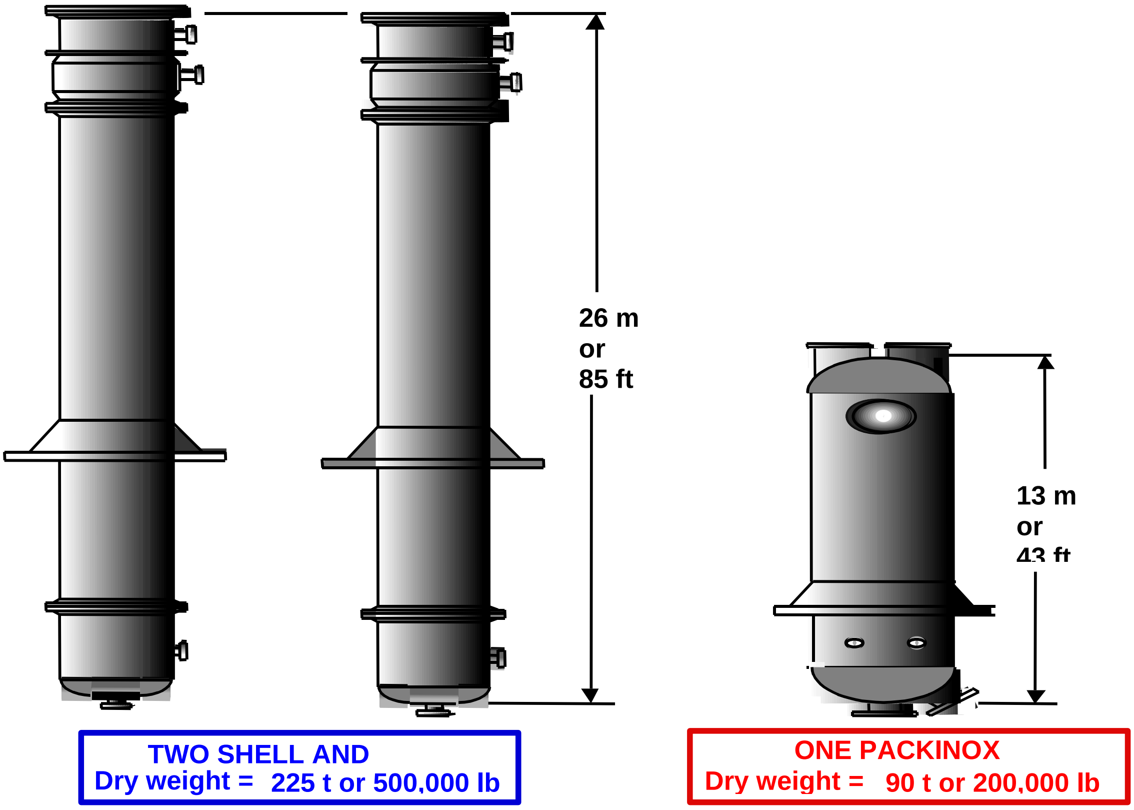

Figure 3.1.3 – Size Comparison between Equivalent Packinox and Shell and Tube Designs (Courtesy of Packinox)

3.1.2.6 Multi-stream and Multi-pass Configurations

Several designs of compact heat exchanger, notably the plate-fin and printed circuit types, can be readily configured for multi-pass and multi-stream applications, while retaining a high effectiveness. This may be coupled with significantly lower pressure drops than would be required in a shell and tube heat exchanger, provided one could be used.

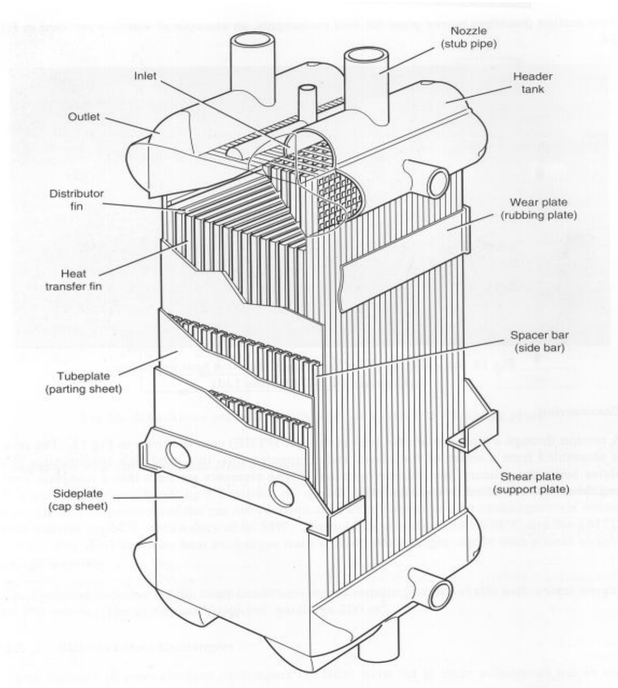

Figure 3.1.4 – Example of a Multi-stream Plate-Fin Heat Exchanger

3.1.2.7 Tighter Temperature Control

A compact heat exchanger allows tighter temperature control. This is often beneficial when dealing with heat-sensitive materials and can lead to improved product quality and consistency.

3.1.2.8 Energy Savings

The ability of compact heat exchangers to operate with smaller driving temperature differences between streams means that it is possible to reduce the power requirements of plant items such as refrigeration compressors that were previously sized for the greater temperature differences required with shell and tube heat exchangers. Energy saving is fully discussed in Module 3.4.

3.1.2.9 Reduced Inventory Volume

Compact heat exchangers operate with much lower fluid inventories (the 'hold-up') than many conventional heat exchangers.

The implications of lower fluid inventories are:

- Safer operating conditions when handling hazardous flow streams.
- Reduced volume when handling highly valuable products.
- Smaller quantities of potentially polluting chemicals may be required for cleaning.

It should be noted that the low hold-up of compact heat exchangers, compared to conventional designs, allows them to react quickly to changes in conditions. This should be taken into account when designing associated control plant and other upstream equipment.

3.1.2.10 Process Intensification and New Applications

The potential for compact integrated reactor heat exchangers is great especially where exothermic reactions are involved. Technology allows the compact exchanger channels to be tailored to the heat and mass transfer needs of the reaction, which in turn allows reaction yield and heat recovery to be maximised and by-product formation to be minimised.

The benefits of this are:

- Reduced energy costs; more efficient removal of heat and less heat loss combined with possible elimination of mixing inefficiencies.
- Reduced capital cost, less material, simpler installation, reduced plant size.
- Safer; smaller inventory, better control, rapid removal of heat of reaction.
- Less waste products; equipment can be better optimised to reduce reaction by-products and reducing the need for downstream processing of products and treatment or disposal of by-products.
- Greater flexibility; in the short term for rapid changes between small quantity, high value process runs and in the medium term for rapid responses to changes in consumer demand.
- Increased throughput and effectiveness of existing processes, or debottlenecking.

3.1.3 Overcoming Limitations of Compact Heat Exchangers

3.1.3.1 Initial Choice Philosophy

When initially selecting heat exchangers for general duties, engineers tend to choose designs on the basis of familiarity and previous experience. Often this means selection of shell and tube designs. However, compact designs operating in appropriate applications can be cheaper to purchase and install as well as delivering more effective heat exchange benefits. In turn this conserves energy for example through higher efficiencies or reduced pumping costs.

Understanding the limitations of compact designs is essential to avoid abortive effort at the initial technology feasibility stage. Such information is readily available from equipment suppliers; for example, Tables 3.1.1 and 3.1.2 show some selection criteria summary for plate heat exchangers and tubular heat exchangers or spiral heat exchangers. More detail on the specification and selection of compact exchangers is given in Module 3.6.

3.1.3.2 Codes of Practice

A lack of standards and Codes of Practice for using compact heat exchangers in the chemical and process industries may have restricted their penetration of the market. More data is becoming available on the long-term mechanical integrity of the newer designs of compact exchanger, largely as a result of the impetus given by the offshore industry, where the incentive to use compact heat exchangers is high.

As compact heat exchangers become more widely known and applied, the barriers to their general application will be reduced. Presenting information on the types of compact heat exchangers now available, their performance range and examples of successful installations should help to overcome one of the main reasons for their currently limited application.

Compact heat exchanger applications are usually designed to conform to internationally recognised practice, such as BS, CODAP, STOOMWEZEN, TUV and ASME, standards depending on the user's specification, together with in-house experience and guidance from equipment suppliers. Some companies rely solely on the vendor for information, although this may not give the contractor or project leader the confidence to explore novel solutions.

HEAT EXCHANGER SELECTION CRITERIA							
	Plate Heat Exchangers				**Tubular Heat Exchangers**		
Physical Properties	**Plate in Frame**	**Plate and Shell**	**Welded**	**Brazed**	**Double Tube**	**Quadruple Tube**	**Multi Tube**
Viscosity							
< 10 CP	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔	✔✔	✔✔✔
< 1000 Cp	✔✔	✔✔	✔✔	✔✔	✔✔	✔✔✔	✔
> 1000 Cp	✔	✔	✔	✔✔	✔✔	✔✔	✔
Shear sensitive particulates							
< 1mm diameter	✔✔	✔	✔	✘	✔	✔✔✔	✔✔✔
< 10 mm diameter	✘	✘	✘	✘	✔✔✔	✔✔	✔✔✔
> 10 mm diameter	✘	✘	✘	✘	✔✔✔	✔	✘
25–37 mm diameter	✘	✘	✘	✘	✔	✘	✘
Insensitive particulates							
< 1 mm diameter	✔✔	✔	✔	✘	✔✔	✔✔✔	✔✔✔
< 10 mm diameter	✘	✘	✘	✘	✔✔✔	✔✔	✔✔✔
> 10 mm diameter	✘	✘	✘	✘	✔✔✔	✘	✔
> 25-37 mm diameter	✘	✘	✘	✘	✔	✘	✘
Fibres							
2 mm	✔✔	✘	✔	✘	✔✔✔	✔✔✔	✔✔✔
15 mm	✔	✘	✘	✘	✔✔✔	✔✔	✔✔
Fluid pressures							
< 1200 kPa (low)	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔
< 2200 kPa (medium)	✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔
> 2200 kPa (high)	✔	✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔
Fluid temperatures							
< 150°C	✔✔	✔✔✔	✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔
> 150°C	✔	✔✔	✔	✔✔	✔✔✔	✔✔✔	✔✔✔
Flexibility for expansion	✔✔✔	✘	✔✔✔	✘	✔	✔	✔
Maintenance	✔✔	✔✔✔	✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔
Ease of Inspection	✔✔✔	✔	✔✔	✘	✔✔	✔✔	✔✔✔
Compactness /floor space	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔	✔

Comparison: - ✔✔✔ = Good selection ✔✔ = Suitable ✔ = Within working range ✘ = Not recommended

Note: The table above is for general comparison of specific characteristics. It is not to be taken as definitive or absolute. For a specific duty more than one property may be relevant leading to a different selection. For optimum heat exchanger selection readers should refer to their equipment supplier.

Table 3.1.1 – Selection Criteria for Plate Heat Exchangers and Shell and Tube Exchangers (adapted from APV information)

HEAT EXCHANGER SELECTION CRITERIA

	Plate Heat Exchangers					Spiral Heat Exchangers	
Physical Properties	**Standard**	**Wide Gap**	**Double Wall**	**Twin Wall**	**Diabon Graphite**	**Spiral Flow**	**Cross Flow**
Service							
Liquid / Liquid	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔	✔
Gas / Liquid	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔
Gas / Gas	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *
Condensation	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔
Vaporisation	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔ to ✔✔✔ *	✔
Nature of Media							
Corrosive	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔	✔
Aggressive	✔	✔	✔	✔✔✔	✔✔✔	✔✔	✔✔
Viscous	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔	✔
Heat Sensitive	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔	✔
Hostile Reactions	✔	✔	✔✔✔	✔✔	✔	✔✔	✔✔
Fibrous	✘	✔✔	✘	✘	✘	✔✔✔	✔
Slurries and Suspensions	✔	✔✔	✔	✔	✔	✔✔✔	✔
Fouling	✔	✔✔	✔	✔	✔	✔✔✔	✔✔
Inspection							
Corrosion	A	A	A	B	A	A	B
Leakage	A	A	A	A	A	A	A
Fouling	A	A	A	B	A	A	B
Maintenance							
Mechanical Cleaning	A	A	A	B	A	A	B
Modification	A	A	A	A	A	C	C
Repair	A	A	A	A	A	(A)	(A)
Fluid pressures							
< 1200 kPa (low)	✔✔✔	✘	✔✔✔	✔✔✔	✘	✔✔	✔✔
< 2200 kPa (medium)	✔✔	✘	✔✔	✔✔	✘	✘	✘
> 2200 kPa (high)	✔	✘	✔	✔	✘	✘	✘
Fluid temperatures							
< 150°C	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔	✔✔✔
> 150°C	✔	✔	✔	✔✔	✔	✔✔✔	✔✔✔

Comparison: - ✔✔✔ = Usually Good selection ✔✔ = Often Good Selection ✔ = Sometimes Good Selection ✘ = Usually unsuitable
A = Both Sides B = One side C = No side

* Depending on operating pressure, gas/vapour density etc.

Note: The table above is for general comparison of specific characteristics. It is not to be taken as definitive or absolute. For a specific duty more than one property may be relevant leading to a different selection. For optimum heat exchanger selection readers should refer to their equipment supplier.

Table 3.1.2 – Selection Criteria for Plate Heat Exchangers and Spiral Exchangers (adapted from Alfa Laval Thermal Division information)

3.1.3.3 Operational Control

Because a compact heat exchanger may be less tolerant of upset conditions than a conventional shell and tube exchanger, a greater degree of monitoring and control is perceived to be necessary if the associated cost savings are to be realised. However, the experience of major compact exchanger users is that any increased operational requirements are of little significance compared with the advantages gained.

3.1.3.4 Concerns About Fouling

The adoption of heat exchangers has been affected by the perception that those with small flow paths are likely to foul.

It is true that care should be taken when selecting compact heat exchangers for use in situations where mechanical cleaning is impossible because of the inaccessibility of the channels in the heat exchanger core. However, gasketed plate heat exchangers are frequently easier to clean than shell and tube types, provided other parameters permit their use.

Where fouling is an issue, methods for minimising fouling in compact heat exchangers include:

- The use of non-fouling fluids wherever possible, such as clean air or gases, lights hydrocarbons and refrigerants.
- The use of self-cleaning strainers, biocides, scale inhibitors, scale removers etc in open systems to reduce fouling.
- The use of self-cleaning filters.
- Chemical cleaning, either by dosing the process stream with additives or by using a separate cleaning loop.
- Employing pulsating flows, reversing the fluids, air rumbling or stopping the cold fluid intermittently.
- Removing and baking the unit in an oven: this is possible when the total heat exchange is achieved by a modular design using relatively small heat exchangers. The foulant residues are then removed by rinsing with water or a detergent.

In some cases the ability of compact designs to achieve better temperature control reduces the fouling risk.

More detailed information on minimising fouling in compact heat exchangers is given in Module 3.2.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.2

FOULING

This module presents general information on heat exchanger fouling. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of the exchanger types, followed by information on the construction, construction materials, operating limits and principal applications.

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FOULING

3.2.1 Introduction to Fouling in Compact Heat Exchangers

Fouling is a generic term for the deposition of foreign matter on a heat transfer surface. Fouling potentially affects all types of heat exchanger.

Deposits accumulating in the small channels of a compact heat exchanger affect both heat transfer and fluid flow.

Fouling deposits constricting passages in a compact heat exchanger are likely to increase the pressure drop and therefore reduce the flow rate. Reduced flow rate may be a process constraint; it reduces efficiency and increases the associated energy use and running costs. Maintenance costs will also increase.

> Fouling remains the area of greatest concern for those considering the installation of compact heat exchangers. The widespread installation of compact heat exchangers has been hindered by the perception that the small passages are more strongly affected by the formation of deposits.

Obviously, compact heat exchangers are unsuitable for fluids containing large particulate material or debris. However, the high shear forces, low wall superheat and homogeneous flow distribution typical of compact heat exchangers reduce the formation and adhesion of deposits on the heat transfer surfaces. Also, the use of more corrosion resistant materials with smoother heat transfer surfaces further reduces the formation of deposits.

Section 3.2.2 examines the generic types of fouling that can occur in heat exchangers and outlines possible solutions. Section 3.2.3 examines the effects of fouling in more detail for different exchanger designs and section 3.2.4 provides further information on minimising the risk of fouling at the specification stage. It is assumed that the specifier of the heat exchanger will have knowledge of the nature of the process stream. However, this will not always be the case, as plant and stream changes can occur some time after units have been installed.

The adoption of heat exchangers has been affected by the perception that those with small channels are likely to foul. Care should be taken when selecting compact heat exchangers for use in situations where mechanical cleaning is impossible. In these cases provision for chemical cleaning must be made. However, gasketed plate heat exchangers are frequently easier to clean than shell and tube types, provided other parameters permit their use.

Figure 3.2.1 - Crystalline (Milkstone) Fouling on a Plate and Frame Exchanger Plate from the Dairy Industry (Courtesy of H. Müller-Steinhagen)

There are two primary problems associated with the small flow passages used in most types of compact heat exchanger:

- The possibility of the heat exchanger acting as a filter for large particles, with these particles forming a filter cake at the inlet to the exchanger.
- The rapid increase in flow resistance resulting from the deposition of only a small thickness of material on exchange surfaces that might pass unnoticed in conventional shell and tube heat exchangers.

The risk of partial blockages turning into complete blockages is also very much higher for compact heat exchangers than for shell and tube heat exchangers, and the difficulty of clearing such blockages, either by mechanical or chemical treatment, is also greater. However, the ability of a compact heat exchanger to filter out material has proved useful in certain applications. In some gas-gas units, the small channel size has caused fibres to collect on the front face of the heat exchanger, instead of in the core where they would be more difficult to remove.

The effect of fouling depends on the deposit location. This, in turn, depends on the fouling mechanism and so on fluid composition. The effects of fouling are likely to be more important for fluid flow than for heat transfer.

For a fluid flow the factors that influence the effect of fouling are:

- The narrowness of the passages, which are relatively easily blocked by particles and fibres.
- The fact that only a small amount of material is required to achieve blockage.
- The difficulty of removing any blockage (although this depends on experience).

Judging the effects of fouling on heat transfer need to take into account:

- The thickness of the deposit, its nature and the area covered.
- The relationship between the clean heat transfer coefficient and deposit resistance.
- The implications for design fouling resistance and the irrelevance of TEMA values.

3.2.2 Types of Fouling and Treatment

For convenience, fouling is generally classified under one of the following six headings, depending on the mechanism causing the deposition:

- Crystallisation or Precipitation Fouling.
- Particulate Fouling (Silting).
- Biological Fouling.
- Corrosion Fouling.
- Chemical Reaction Fouling.
- Freezing or Solidification Fouling.

3.2.2.1 Crystallisation or Precipitation Fouling

Crystallisation or precipitation fouling occurs when a solute in the fluid stream is precipitated out and crystals are formed, either directly on the heat transfer surface or in the fluid, and subsequently deposited on that surface. When the fluid concerned is water, calcium or magnesium salts are deposited, frequently referred to as scaling. Figure 3.2.1 shows a plate fouled by crystalline calcium phosphate deposits.

For normal solubility salts (e.g. sodium chloride), this type of fouling decreases with increasing heat transfer surface temperature, as the solubility increases. For the more troublesome inverse solubility salts (e.g. calcium sulphate, calcium phosphate, calcium silicate, calcium carbonate, magnesium hydroxide and magnesium silicate), the solubility decreases with increasing temperature. Hence, these salts are prone to forming deposits on surfaces where heat is transferred to water, either during cooling or evaporation.

It is important to identify the highest cooling water temperature that is likely to occur in a heat exchanger with narrow channels to determine the appropriate water strategy.

Solution

Crystallisation or precipitation fouling is normally avoided either by pre-treating the fluid stream (e.g. by adding acid to cooling water to remove bicarbonate) or by the continuous addition of chemicals to reduce or eliminate deposit formation.

If deposits do form, they can often be removed by treatment with appropriate chemicals, e.g. by adding acid to remove carbonates. Care must be taken to ensure that the cleaning chemicals are compatible with the construction materials used for the exchanger.

Mechanical methods, such as the high-pressure lances that are often used to clean shell and tube heat exchangers, are unlikely to be of use for compact heat exchangers because of their small passage size.

3.2.2.2 Particulate Fouling (Silting)

Particulate fouling (or silting) occurs when solid particles from the fluid stream are deposited on the heat transfer surface. Most streams contain some particulate matter, originating from a variety of sources. Small particles are less likely to be removed from the surface than large ones. The combination of particles with condensation or other sticky forms of fouling can produce a deposit that is much more adhesive and difficult to remove than the individual components on their own. An example would be a combination of paper fibres and polymer adhesive from ink in a printing works heat recovery unit.

A particulate deposit may also provide a mechanism for keeping a surface wet. This may have implications for corrosion (e.g. the formation of an acid condensate from combustion gases).

Solution

Purely particulate fouling can be reduced by the use of sufficiently high fluid velocities. If the deposit also contains matter that acts as an adhesive, a solvent or other chemical treatment will be required to remove the adhesive. Chemical dispersants that affect the surface charges on solids can also assist in avoiding deposit formation.

Mechanical removal, e.g. by brushes, may be feasible, if access is available. Air rumbling, i.e. the temporary addition of air or of nitrogen to the liquid stream is frequently used to dislocated particulate or biological deposits.

Larger particles can easily be filtered out, and a suitable strainer could be located upstream of a compact heat exchanger where such particles are expected. The application of a severe pressure pulse can remove silting, but its effect on the mechanical strength of the exchanger must be considered.

Several other factors alleviate fouling in compact heat exchangers. The use of corrosion-resistant materials minimises fouling by upstream corrosion products and the specific design of compact heat exchangers gives high wall shear stresses. Designers should ensure that there are no flow dead spots.

3.2.2.3 Biological Fouling

The deposition and growth of organisms on surfaces cause biological fouling. The organisms most likely to cause problems in compact heat exchangers are bacteria, which can thrive even if the concentration of nutrients in the water is less than one part per million.

Bacteria grow over a wide range of temperatures. Bacterial growth may physically constrict flow passages or can generate a corrosive environment (e.g. sulphate reduced to hydrogen sulphide is corrosive to most materials, including common stainless steels).

Figure 3.2.2 - Reaction Fouling (Protein Deposition) on a Plate and Frame Exchanger Plate (Courtesy of H. Müller-Steinhagen)

Solution
Biological fouling is best controlled by treatment with biocides.

Non-oxidising biocides are normally alternated to prevent the development of bacterial deposition. Certain biocides kill the bacteria, but do not remove the biofilm accumulation, but some are available with detergent properties that disrupt the film. Oxidising biocides, such as chlorine and ozone, oxidise the biofilm as well as killing the bacteria and may therefore require higher concentrations to be effective.

Compared with a conventional shell and tube exchanger, the relatively low surface area and the lower fluid inventory in a circuit with a compact heat exchanger should reduce the amount of biocide required. The well-defined flow in the small channels also aids rapid diffusion of the treatment chemical to the biofilm.

3.2.2.4 Corrosion Fouling
Corrosion fouling results from either a chemical reaction involving the heat transfer surface, or the transportation of corrosion products from elsewhere in the circuit and their deposition in the heat exchanger. Corrosion can also take place under the deposits, e.g. as a result of the formation of electrolytic oxygen concentration cells.

Solution
Corrosion fouling is best minimised at the specification stage by choosing materials that are resistant to corrosion in the fluid stream whenever possible. Alternatively, it is possible to dose with corrosion inhibitors, although the environmental impact of this approach must be considered. Cathodic protection can also be used, but care must be taken to ensure that the conditions do not form cathodic scales (calcium and magnesium salts) in hard waters and brines.

If a stainless steel heat exchanger is stored in a moist, salt-laden environment, measures should be taken to protect the surfaces. Amounts of salt as low as 1.0 mg/l could result in stress corrosion cracking.

Compact heat exchangers are usually made of the more corrosion-resistant materials. Several types have no dissimilar metals or other materials present, making corrosion attack on the heat exchanger surfaces predictable, unless unforeseen impurities are present in the fluid streams.

3.2.2.5 Chemical Reaction Fouling
Chemical reaction fouling occurs when one or more constituents in the process fluid react to form a viscous or solid layer on the heat transfer surface, which is not itself involved in the chemical reaction. Such reactions are mostly polymerisations, and the deposit that is initially formed may turn from a tar to a hard coke or similar material that is more difficult to remove.

Figure 3.2.2 shows protein fouling of a plate exchanger from the dairy industry.

Solution

The rate of chemical reactions increases exponentially with temperature, making it possible to minimise chemical reaction fouling by careful control of fluid and surface temperatures and by reducing residence times at high temperatures. Temperatures should not be increased to achieve the required heat transfer as this will make the fouling problem rapidly worse. It should be much easier to control chemical reaction fouling in a compact heat exchanger than in a conventional shell and tube exchanger because of the high degree of temperature control and low residence times. Compact heat exchangers have lower hold-up and residence times than conventional shell and tube exchangers.

3.2.2.6 Freezing or Solidification Fouling

Freezing or solidification fouling occurs when the temperature of the process fluid is reduced sufficiently to cause freezing at the heat transfer surface.

Solution

This type of fouling is the easiest to control, particularly in compact heat exchangers, where the small mass and low fluid inventory allows rapid clearance of the fouling by increasing the temperature to melt the deposit. In some cases, channels may be incorporated in the exchanger to allow a hot fluid stream to be introduced to melt material, such as hydrates.

Compact heat exchangers offer a closer temperature approach and greater control over stream temperature.

3.2.3 The Fouling Resistance (R_f)

In the thermal design of heat exchangers, fouling is conventionally taken into account by using an additional thermal resistance value, R_f, called the 'fouling factor' or 'fouling resistance', when calculating the overall heat transfer coefficient. Fouling reduces the overall heat transfer and, for a given duty, extra surface has to be provided to ensure that the required heat transfer is achieved.

In most cases fouling resistance is time dependent, with zero fouling initially. Frequently fouling resistance builds up to an equilibrium point where the rate of foulant removal is equivalent to the rate of deposition. Depending on the value of this 'asymptotic' fouling resistance, this may or may not allow continuous operation without cleaning. Alternatively, fouling resistance may continue to increase necessitating a cleaning action at some point.

Thermal resistance values are often taken from the standards recommended by TEMA. These are dedicated to shell and tube heat exchangers and, as such, are generally not applicable to compact heat exchangers. Using the TEMA values is likely to result in excessively high additional surface requirements. This is because the implied deposit thickness may give very high pressure drops in small channels. It is generally found that much lower fouling resistances than those recommended by TEMA can be used for plate and frame heat exchangers.

Measures such as filters to avoid compact heat exchanger blockages have encouraged some industries (e.g. the cryogenics industry) to adopt fouling resistance values of zero. Some manufacturers may add 10 - 25% extra surface to allow for uncertainties in design codes and other factors, of which fouling may be one. This should not be used as an excuse to reduce the flow velocity.

3.2.3.1 Fouling in Plate and Frame Exchangers

Plate and frame heat exchangers were originally developed for the dairy industry. However, their application in the chemical process industry is increasing rapidly, where they begin to replace tubular heat exchangers in several traditional applications. While there is plenty of information about the governing equations for clean operation, information for fouling conditions is scarce. As shown in the following equation the percentage excess surface area increases with increasing clean heat transfer coefficient for a given heat duty.

$$\frac{A_f}{A_c} = 1 + U_{clean} \qquad R_f$$

Where:

A_f	is the surface area after fouling
A_c	is the clean surface area
U_{clean}	is the clean heat transfer coefficient
R_f	is the fouling resistance

This puts a heavy penalty on compact heat exchanger types such as plate and frame heat exchangers if, because of ignorance or because of cautiousness, the TEMA fouling resistances for shell and tube heat exchangers are used. Typical clean overall heat transfer coefficients for plate and frame heat exchangers are about 3000 W/m^{2}K, for shell and tube heat exchangers about 1000 W/m^{2}K. A design fouling resistance of 0.3 m^{2}K/kW corresponds to 30% overdesign for a shell and tube heat exchanger and to 90% overdesign for a plate and frame heat exchanger. Most manufacturers of plate and frame heat exchangers recommend that the excess surface should not exceed 25% of the heat transfer surface area calculated for the clean duty.

The fouling resistances listed in Table 3.2.1 have been recommended for plate and frame heat exchangers. Due to the non-uniformity of flow distribution and deposit formation, measured pressure drop increases are significantly higher than values predicted using an average deposit thickness calculated from the fouling resistance.

Fluid	Fouling Resistance (m^2K/kW)
Water	
demineralised or distilled	0.009
soft	0.017
hard	0.043
treated cooling tower water	0.034
coastal sea water	0.043
ocean sea water	0.026
river water	0.043
engine jacket	0.052
Lubricating oil	0.017 - 0.043
Vegetable oil	0.017 - 0.052
Organic solvents	0.009 - 0.026
Steam	0.009
General process fluids	0.009 - 0.052

Table 3.2.1 - Fouling Resistances for Plate and Frame Heat Exchangers[1]

Effect of Process Parameters on Fouling

Cooper[2] investigated cooling water fouling using a plate heat exchanger. The water was chemically treated before entering the heat exchangers. Some of the important results of this investigation are given in Figure 3.2.3.

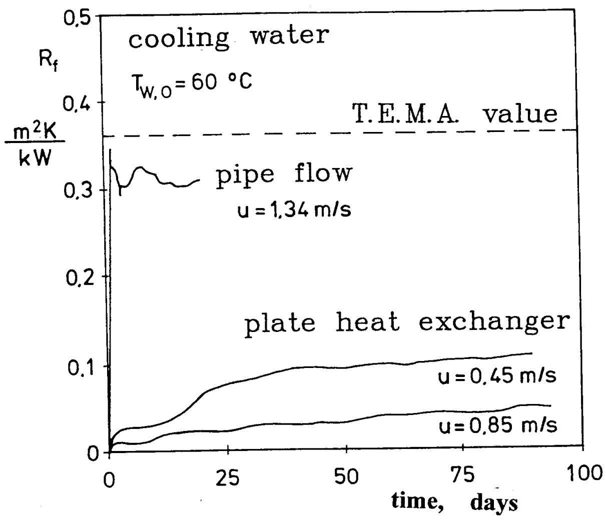

Figure 3.2.3 – Comparison of Fouling in Plate and Frame, and in Shell and Tube Heat Exchangers (after Cooper)

The fouling resistance in the plate and frame heat exchanger is significantly lower than in the shell and tube heat exchanger, despite the typically lower flow velocities. If the flow velocity is increased, the fouling resistance decreases similarly as it is found for shell and tube heat exchangers. This is also demonstrated in Figure 3.2.4 which shows the asymptotic value as a function of the surface temperature halfway up the plates.

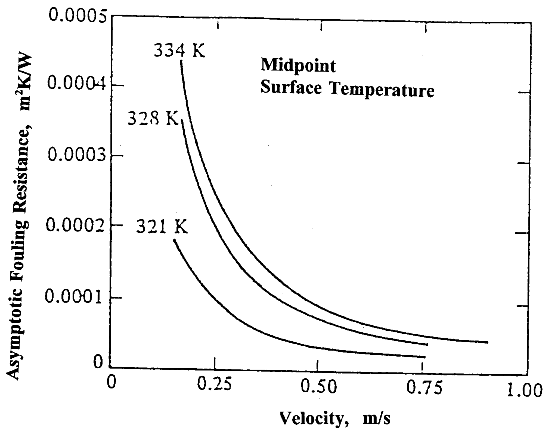

Figure 3.2.4 – Fouling Resistance in a Plate and Frame Heat Exchanger as a Function of Flow Velocity and Temperature (After Cooper)

Novak[3] studied the fouling behaviour of Rhine River water near Mannheim (Germany), and of Öresund seawater in Sweden. For both waters, mainly biological fouling was observed. The fouling resistances increased almost linearly over the period observed. Table 3.2.2 summarises the effects of flow velocity on fouling rates.

Type	**u m/s**	**t Pa**	**dR_f/dt 10^4 m^2K/kWh**
Plate heat exchanger	0.13	6.7	7.4
Plate heat exchanger	0.19	14.5	4.3
Plate heat exchanger	0.77	190.0	0.6
Spiral plate exchanger	0.43	7.5	5.0

Table 3.2.2 - Fouling Rates of Rhine River Water for a Surface Temperature of 25°C[3]

For constant flow velocity, Novak found that maximum fouling occurred at a surface temperature of about 35°C, due to the preferred living conditions of biological matter.

Bansal and Müller-Steinhagen[4,5,6] investigated pure crystallisation fouling from $CaSO_4$ in various plate heat exchangers. The rate of deposition increases with increasing wall temperature and bulk concentration and decreasing velocity. With increasing flow velocity, both the initial fouling rate as well as the absolute value of the fouling resistance decreases. Due to blockage of the outlet flow distribution area, the increase in pressure drop may be significantly higher than the increase in thermal fouling resistance.

Chemical reaction fouling is strongly affected by the surface temperature that determines the reaction rate.

Effect of Plate Design

Two low velocity zones exist in the plate channels, opposite to the inlet and outlet ports. In these zones, shear forces are at a minimum and the wall temperature is close to the temperature of the heating medium. Both conditions promote the formation of deposits. The extent of the stagnant zones depends on the design of the flow distribution section. It decreases with increasing flow velocity.

Kho[7] studied the various possibilities of providing excess heat transfer surface area for fouling. Figure 3.2.5 shows that minimum fouling occurs if the 20% excess surface area is provided by a two-pass arrangement of the original plates, followed by the use of larger plates with the same width, followed by larger plates with standard width/height ratio. The poorest performance is obtained when the excess surface is simply added as parallel plates.

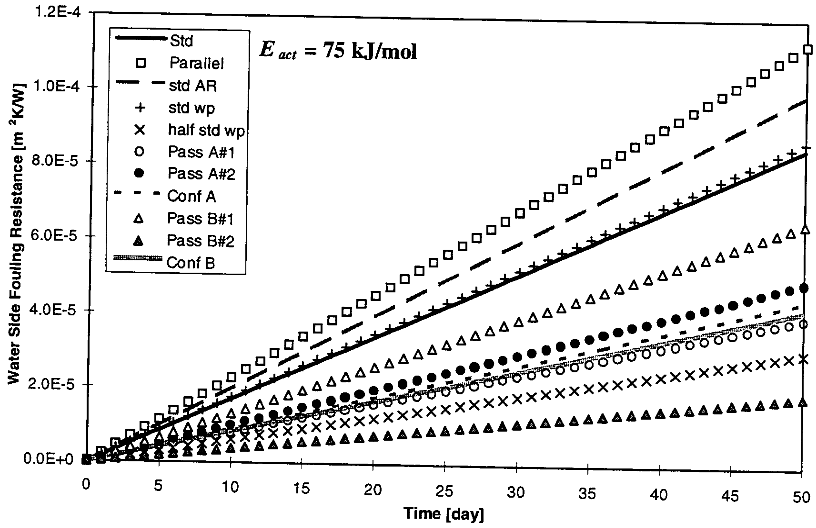

Figure 3.2.5 – Effect of Plate Arrangement on Fouling (After Kho)

The actual plate geometry (angle, amplitude and wavelength of corrugations) affects the formation of deposits. Delplace et al.[8] found that deposition from whey protein solutions on herringbone plates is only half of that of straight corrugations, for otherwise identical conditions.

Plate heat exchanger designs with extra-wide plate gap are available for applications with significant particulate content or severe fouling.

For all types of fouling, the delay time decreases with an increase in surface roughness. Heat exchanger plates usually have smoother surfaces than pipes, because of the manufacturing process itself and because the lower area requirement allows more expensive surface preparation. Electropolished plates with a surface roughness below 0.5 µm are commercially available, and are commonly used in food processing industries. Investigations with plate surfaces modified by Magnetron Sputtering, Physical Vapour Deposition and other technologies which can provide low surface energies are presently underway[9, 10].

3.2.3.2 Fouling in Plate-Fin Heat Exchangers

Plate-fin heat exchangers are brazed/welded compact heat exchangers with a heat transfer surface density of about ten times that of tubular heat exchangers. Typical applications are cryogenic, chemical/petrochemical and hydrocarbon offshore installations. Molecular sieves and 100 μm filters are used in cryogenic installations to remove particulate matter or components that may freeze-out on the heat transfer surfaces.

Systematic investigations have been performed on particulate fouling(11) and on river water fouling(12).

For 3 μm ferric oxide particles suspended in water, no blockage of plain fin or wavy fin channels was observed. Wavy fin channels fouled more than plain fin channels. All experiments showed asymptotic behaviour. Higher deposition rates were obtained for non isothermal conditions and at higher bulk temperatures. Maximum deposition occurred at a Reynolds number of about 1500.

Fibrous and biological material partially blocked the inlet of the aluminium plate-fin test sections when used with river water that was filtered through a 1 mm mesh. Some deposition was found at locations where corrosion of the aluminium had occurred. In the wavy fin test section, a thin, uniform deposit of fine mud was observed. Pressure drop for the plain finning increased linearly with time, whereas asymptotic behaviour was found for the wavy finning. The initial slope of the relative pressure drop versus time curves was $5.8\text{x}10^{-8}$ s^{-1} for the plain fins and $1.71\text{x}10^{-7}$ s^{-1} for the wavy fins. For the latter, an initial deposition rate of $4.8\text{x}10^{-12}$ and an asymptotic fouling resistance of $6\text{x}10^{-6} m^2K/W$ were measured.

3.2.3.3 Fouling in Printed Circuit Heat Exchangers

The passages in printed circuit heat exchangers are typically between 0.3 mm and 1.5 mm deep. This specific design leads to volumetric heat transfer areas of 500-2,500 m^2/m^3, which is an order of magnitude higher than shell and tube heat exchangers.

Two sets of experiments are described by Kew(13) to compare the fouling related drop in performance of a printed circuit heat exchanger and of a double pipe heat exchanger:

1. Cooling water treated against corrosion, scale formation and biofouling, and with 0.5/1.0 mm strainers to reduce particulate fouling. For operating times of 500-660 hours, no change in thermal effectiveness was observed for the printed circuit heat exchanger, but the pressure drop increased by up to 55% due to the deposition of particulate material. The addition of a stainless steel mesh insert for the removal of fibrous material significantly reduced the increase in pressure drop. No deposition was observed in the parallel double pipe heat exchanger.

2. Cooling water treated against corrosion, biofouling and particulate fouling, but supersaturated to induce scaling. In tests between 100-290 hours, the thermal effectiveness again remained constant. The printed circuit heat exchanger pressure drop increased by up to 30% due to the formation of calcium carbonate and calcium phosphate. Pressure drop and thermal effectiveness in the double pipe heat exchanger remained constant.

These experiments suggest that thermal effectiveness in printed circuit heat exchangers is not linearly related to pressure drop and that fouling must be carefully considered when selecting printed circuit heat exchangers.

Where printed circuit heat exchangers have been used for gas cooling using sea water, 200 µm strainers have been installed upstream of the heat exchanger and chlorine added to counter biofouling. No operational problems have been reported.

Another application involved the heating of tail-gas in a nitric acid plant using condensing steam; after 18 months of operation, no indication of channel blockage could be detected.

3.2.3.4 Fouling in Polymer Compact Heat Exchangers

Polymer heat exchangers are used for low pressure operations involving corrosive gases or liquids. The low surface energy and the smooth surface of their construction materials (polypropylene, fluoropolymer etc.) reduce the stickability of most deposits. Since clean heat transfer coefficients are already low (150-250 W/m^2K), these heat exchangers react less sensitively to additional fouling resistance than metallic heat exchangers.

3.2.4 Preventing Fouling Effects

3.2.4.1 Design Stage

Identify at an early stage the extent to which process streams are likely to cause fouling.

The following points give general guidance.

<u>Circuit Configuration</u>

Closed loops are unlikely to present significant fouling problems. Working fluids in refrigeration or power cycles, for example, should not cause any fouling in a well-engineered and maintained system.

Open loops are prone to fouling, and may require the installation of filters to remove particles, fibres etc., as well as regular chemical treatment to prevent biological growth, the deposition of scale, and corrosion. In open systems, check the possibility of using self-cleaning strainers and of installing systems for biocide dosing, the application of scale inhibitors, etc., to control fouling.

Once-through streams need to be examined on a case-by-case basis and appropriate action taken if the stream warrants it.

If water treatment is constrained by environmental concerns, consider installing an untreated primary cooling water circuit with a secondary clean circuit serving the plant. The other benefits of compact heat exchangers may make this worthwhile.

Where a closed cycle system is not an option, consult with the equipment supplier(s) and give detailed consideration to:

- Fouling margins.
- Optimal flow rates.
- Control of heat exchanger operation.
- Upstream fouling prevention.
- In-exchanger fouling control/removal.

Alternatively consider a specific compact exchanger design able to handle the fouling projected.

Performance Monitoring

On larger installations, or where an exchanger duty is critical for a process, exchanger monitoring can give early indication of cleaning thresholds or failure conditions. Monitoring can either be continuous or intermittent as necessary.

Progressive fouling will become evident by increases in the pressure drop through the heat exchanger. It is also essential to measure the stream flow rate because a pressure drop increase may be compensated by reduced flow.

Inlet and outlet stream temperatures may also be measured. In some cases it may be useful to calculate heat transfer coefficients on a regular basis from the parameters measured above.

Particulate Fouling

Reputable equipment suppliers should know the tolerance of their heat exchangers to particulate fouling. If they recommend filtering down to 100 microns, accept this. Subsequent problems are likely to be caused by neglecting to replace filters, or by changing stream conditions outside the limits set initially.

If a new plant is being installed, try to build cleanliness, and the measures to maintain it, into the whole process philosophy. This may involve locating filters at the main plant inlet streams. Alternatively, make sure there is provision for removing the individual filters on each heat exchanger for cleaning. Use self-cleaning filters if possible.

Fluid Velocity

Fluid velocity has an effect on fouling. Any reduction in velocity associated with a lower throughput may increase fouling and necessitate more frequent heat exchanger cleaning. Take this into account when considering the operational flexibility necessary for the process.

Modular Design

Wherever possible, adopt a modular design that uses relatively small heat exchangers. These units can be individually removed for cleaning without total process shutdown. Installing multiple heat exchangers will have economic implications to be considered during design and specification including additional piping complexity.

Cleaning

Where a compact heat exchanger cannot be disassembled for mechanical cleaning (e.g. welded, brazed or diffusion bonded heat exchanger cores), install filtration equipment upstream. Another alternative is to consider chemical cleaning, possibly using a separate cleaning loop.

If chemical cleaning is to be used, ensure that:

- The system is designed to allow the introduction and complete removal of the cleaning fluids used (no dead-legs).
- The cleaning fluids are compatible with the compact heat exchanger and associated pipework over the full temperature range.

In extreme circumstances small exchangers can be baked in an oven enabling the burnt fouling to be removed by rinsing with water or a detergent. Baking to remove serious fouling is unusual, as heating temporarily to such high temperatures will damage most heat exchangers.

Hydraulic Measures

Pulsating flows, reversing the fluids, or stopping the cold fluid intermittently can inhibit some types of fouling, but expert advice should be taken before adopting such techniques, as they can make some fouling problems worse. Air rumbling, i.e. the temporary addition of air or of nitrogen to the liquid stream is frequently used to dislocate particulate or biological deposits.

Cleaning-in-Place Plants

Automatic cleaning-in-place (CIP) plants can be linked to a process plant for cleaning pipes, tanks and heat exchangers internally. Figure 3.2.6 shows the layout of a typical CIP plant.

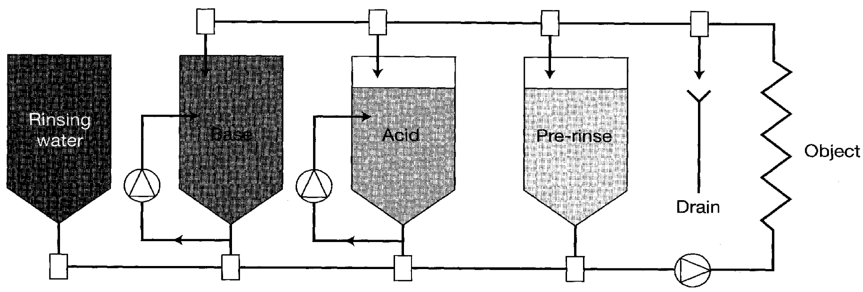

Figure 3.2.6 - Layout of a Typical CIP Plant

A typical CIP procedure takes place in five stages:

- A pre-rinse with cold water, helping to displace the product in the system.
- A rinse in an alkaline solution at approximately 80°C.
- A rinse in cold water.
- A rinse in acid solution at approximately 70°C.
- A rinse in cold water.

The cleaning time required depends on the equipment being cleaned and the fluids and temperatures used: it varies from thirty minutes for tanks to five hours for evaporators. In some cases, cleaning time may be reduced by introducing a short acid rinse prior to the alkaline cleaning, thereby helping to remove possible mineral deposits. Single-pack chemicals are also available that remove protein and mineral deposits at the same time.

CIP may be used for removing many types of fouling, including biological slime, rust, scale and organic matter. An example of the efficiency of CIP in removing cooling water deposits is shown in Figure 3.2.2. In this example, biological fouling from Rhine river water was removed by a slowly circulating alkaline solution at 60°C[3].

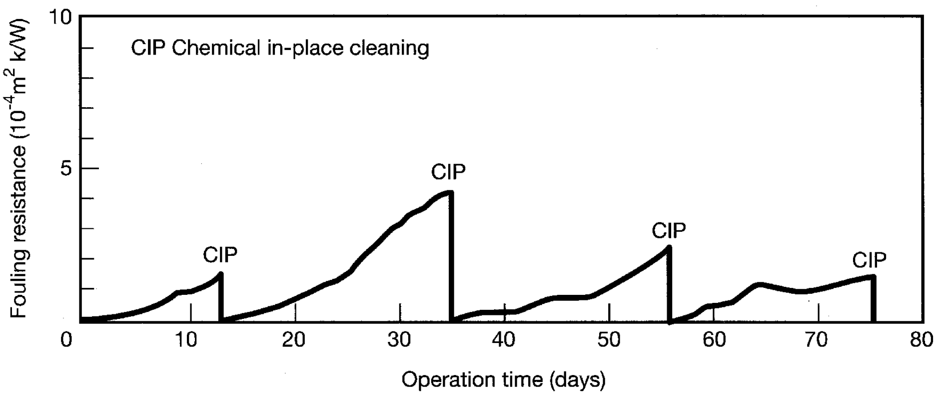

Figure 3.2.7 – Reduction of Fouling Resistance by CIP (after Novak)

Typically spent CIP solutions must be treated before release to the environment or recovered for reuse.

3.2.4.2 Installation

If fouling is likely to reduce the run time of a compact heat exchanger, consider installing two identical units in parallel. If one becomes fouled, the flow can be diverted through the other. The principle is the same as incorporating a bypass on a waste heat recovery unit to permit cleaning or to avoid plant shutdown in the event of a failure.

Take extra care when installing, hydraulically testing and commissioning to avoid fouling and possibly corrosion.

3.2.4.3 Operation and Maintenance

Effective operational experience includes the following.

Check Design Limitations

Be aware of the design limitations of the selected compact heat exchangers. A tight design can limit operational flexibility, and optimum performance and minimum fouling will only be achieved when the unit is operated at, or near, its design conditions. For instance any reduction in the velocity of a cooling water stream may increase fouling.

Adequate Training
Make sure that all staff are fully trained in compact heat exchanger operation. Failures have occurred where non-specialists in heat exchangers were unaware of operating practices and experience.

Routine Preventive Maintenance
Compact heat exchangers are more vulnerable to the effects of fouling or blockage than conventional shell and tube heat exchangers. Therefore, give the same high priority to the relevant preventive measures - filters, chemical dosing etc. - as to ensuring that equipment, such as the main pumps, remains serviceable.

Failure or Blockage Procedures
Establish clear procedures for failure situations.

When a failure occurs during operation, the general rule is to contact the manufacturer as soon as possible.

Mechanical failure during operation may occur because liquids freeze or because of over-pressurisation, explosion, damage etc. If any of these occur, contact the manufacturer to discuss the possibilities of repair.

Decide on contingency plans for dealing with a blocked compact heat exchanger, such as cleaning in situ, blocking off the affected layers of a plate-fin heat exchanger, or switching to standby/replacement units.

The mechanical failure of one or more layers in a plate-fin heat exchanger or similar type of compact design need not involve complete replacement. Layers may be blanked off to allow continued operation. In some designs up to 10% of the layers may be blanked off. However, you should consult your equipment supplier before proceeding in this way.

Overhaul Procedures
Establish clear maintenance and overhaul procedures.

Some compact heat exchangers can be sent off-site to be overhauled. This is particularly beneficial in the case of gasketed plate heat exchangers, as the gaskets are refitted to manufacturers' standards.

If heat exchangers with gaskets are reassembled on site, ensure uniform gasket compression to minimise the risk of leaks. Use gaskets supplied by the heat exchanger manufacturer.

With all reassembly, it is important to ensure that the manufacturer's recommendations are followed.

3.2.5 References

A full list of references is given in section 5.1.4.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.3

APPLICATIONS

This module outlines the experience of using compact heat exchangers in various sectors of industry. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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- 3.3.1.3 Cryogenics
- 3.3.1.4 Food and Drink
- 3.3.1.5 Paper and Board
- 3.3.1.6 Textiles and Fabric Care
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APPLICATIONS

3.3.1 Using Compact Heat Exchangers in the Process Industries

This Module outlines the experience of using compact heat exchangers in various sectors of the process industry. For more detailed application information, enquirers should contact equipment suppliers.

Today compact heat exchanger designs are used for many applications in process industries, as summarised in Table 3.3.1. Of course, applications are process specific with different exchanger designs being used for different processes. Further information on the generic applications is given in Section 3.3.2.

Process Industry Sector	Distillation	Evaporation	Reactor	Separations	Compressors	Refrigeration	Mechanical Vapour Recompression
Chemicals and petrochemicals	✔	✔	✔	✔	✔	✔	✔
Pharmaceutical	✔	✔	✔	✔	✘	✔	✘
Cryogenics	✔	✔	✘	✘	✔	✔	✘
Food and drink	✔	✔	✘	✘	✔	✔	✔
Paper and board	✘	✘	✘	✘	✔	✘	✘
Textiles	✘	✘	✘	✘	✔	✘	✘
Oil and gas processing	✔	✔	✔	✔	✔	✔	✔

Notes:

✔ - Compact heat exchanger application track-record

✘ - Compact heat exchangers generally not suitable

Table 3.3.1 - Compact Heat Exchanger Applications in Process Industry Sectors

3.3.1.1 Chemicals and Petrochemicals

The chemicals and petrochemicals sector uses the full range of compact heat exchangers across its wide range of processes.

They are used in certain ‘standard’ products, for example compact cores in kettle reboilers and plate-fin dephlegmators, used for partially condensing/purifying fluids in applications such as ethylene recovery. There are also ‘one-off’ uses, for example application of the printed circuit heat exchanger as a nitric acid plant tail-gas heater and as a compact economiser.

Although the conditions under which many of these processes operate would appear to limit the use of compact designs, there are numerous instances where compact heat exchangers have replaced more conventional equipment. Other compact unit operations, reactors in particular, also employ compact heat exchanger technology.

3.3.1.2 Pharmaceuticals

The pharmaceutical industry uses batch processes extensively, and compact heat exchangers often form part of the plant. A typical application would involve a plate and frame heat exchanger on a heat-cool-chill process, transferring heat indirectly to reaction masses. Batch plant needs to be rapidly and thoroughly cleaned with each product change. It is therefore preferable to use heat exchangers with no dead spots where product can accumulate.

3.3.1.3 Cryogenics

Providing nitrogen, oxygen and argon is an energy-intensive operation that needs heat exchangers capable of multi-stream operation at very low temperatures with close approach temperatures. The capital and operating costs associated with thermodynamic irreversibilities increase as the processing temperature falls, so one of the prime aims of heat transfer in cryogenics is to minimise these irreversibilities.

Plate-fin heat exchangers can meet these requirements and minimise heat gains from the environment. Their ability to accommodate many process streams and their robust aluminium construction makes them even more attractive, and they have found widespread application in cryogenics.

It is important to prevent the freezing of components, such as carbon dioxide and water, and to limit corrosion by mercury, acid gases etc. The former can largely be achieved by removing the relevant components upstream using molecular sieves, while particulates can be filtered out, typically using physical filters of 100 µm or less. However, older plant tends to rely solely on filters, using reversing (freezing/unfreezing) to remove solidified components. The exchangers used in such plant can ultimately fail as a result of corrosion. Pre-treatment is a successful way of overcoming these problems, the only reservation being that any perlite insulation dust present upstream of the heat exchanger can affect performance during construction/start-up.

3.3.1.4 Food and Drink

The food and drink sector pioneered the use of the plate and frame heat exchangers. Plate and frame designs are used increasingly in evaporators and are an integral component of 'compact' evaporators, which are normally of the mechanical vapour compression type (see Section 3.3.2.2). They are also used in edible oil processing.

Figure 3.3.1 – Paraflow Plate Heat Exchanger
(Courtesy of APV)

3.3.1.5 Paper and Board

Opportunities for using compact heat exchangers in the paper and board sector are limited, unless radical process changes allow new uses in the future. However, it is currently feasible to use plate and frame exchangers to recover heat from the dryer when a spray condenser is used as the primary heat exchanger. Compact heat exchangers may also be used in combined heat and power plants.

Experiments using 65% solids black liquor from a New Zealand pulp mill have demonstrated that plate and frame heat exchangers can operate significantly longer than tubular heat exchangers(1).

Fluidised bed heat exchangers have proved valuable in applications where fouling would prevent the use of heat exchangers with small channels, for example in processing white water that contains paper stock. Experience in Scandinavia and the USA suggests that wide-gap plate and frame exchangers can be cost-effective, and spiral heat exchangers can also be used in this application.

3.3.1.6 Textiles and Fabric Care

One of the relatively few applications of compact heat exchangers in the material production sector is in the spinning of acrylic fibre from an extremely viscous dope.

Conventional cooling equipment is unsatisfactory in this environment because of the wide variation in viscosity over the temperature range involved. A much closer temperature control can be achieved using plate and frame exchangers, and their greater efficiency allows mains water rather than chilled water to be used.

Plate and frame exchangers have become established over the last decade for use on most liquid effluents in textile dyeing and finishing, and in fabric care. Their close approach temperatures and the easy access for cleaning (gasketed types) makes them very cost-effective. Filters are commonly fitted upstream to remove gross contamination.

3.3.1.7 Oil and Gas Processing

Plate and frame heat exchangers are used both onshore and offshore for low-pressure duties, while brazed-plate units can be employed at higher pressures. Welded plate heat exchangers are used extensively in gas dehydration regeneration systems (rich triethylene glycol / lean triethylene glycol exchangers). They are also used in gas desulphurisation regeneration systems for amine/amine heat transfer and can even replace shell and tube units for crude oil heating. Where the safety of gasketed plate and frame heat exchangers might be a concern, welded compact heat exchangers would be a logical choice.

Printed circuit heat exchangers and diffusion-bonded plate-fin heat exchangers are used offshore for high pressure and export gas cooling where gas pressures can exceed 400 bar and sea water is used for cooling. Compressor aftercoolers based on printed circuit heat exchangers are in use up to 400 bar, and other offshore printed circuit heat exchanger applications are listed in Table 3.3.2.

Thermal Duty	Pressure (bar)	Use	Comments
6 off to 17.8 MW	97.6 – 307	Gas/gas and coolers	Major project – gas processing heat exchangers
2 off to 1.6 MW	102 – 225	Gas/gas and cooler	Export cooler constructed in titanium for direct sea water cooling
2 off 0.173 MW	400	Coolers	HP fuel gas compressor aftercoolers
6 off to 29 MW	45 – 200	Coolers and heaters	Major project exchangers - substantial deck cost reduction
2 off to 3 MW	35	Gas/gas/gas-liquid	High pressure, counter-flow, multi-stream, multiphase

Table 3.3.2 - Offshore Printed Circuit Heat Exchanger Applications

For corrosion resistance under these conditions, the heat exchangers are normally made of titanium. For example, titanium plate-fin exchangers are used on a North Sea gas production platform to provide direct seawater cooling of product. These units will have a duty of 12.1 MW and operate at 125 bar.

In the future, the manufacturers of both printed circuit heat exchangers and superplastically formed plate-fin heat exchangers foresee units operating at more than 500 bar with temperatures of up to 400^{o}C. Duplex stainless steel printed circuit heat exchangers are already available and plate-fin exchangers of the same material will be available in the future.

Companies have made significant energy and capital cost savings by using plate-fin exchangers as reflux exchangers to perform simultaneous heat and mass transfer operations.

There are possible new uses in hydrocarbon dewpoint control, condensate recovery, etc., while other applications include liquefied natural gas sub-cooling and cryogenic distillation, for example for nitrogen removal.

Extra protection needed when operating offshore can be expensive and can necessitate extensive modifications during retrofits or when new regulations are brought into effect.
For example, where a shell and tube heat exchanger is used, a relief system is necessary to cope with a possible tube rupture i.e. the high-pressure system discharges into a low pressure one. Relief provision for a conventional heat exchanger would have required extensive modification; however, because a printed circuit heat exchanger with a much smaller hold-up capacity was used, it was possible to provide only the relief needed in the case of fire or other emergency.

When used offshore, plant, including heat exchangers, requires mandatory external protection systems, including fireproof containment structures. So compact heat exchangers have lower inventories, require less containment and therefore are cheaper.

Compact heat exchangers are not yet widely used in onshore refineries. One company reported that only 1 to 2% of refinery heat exchangers are compact heat exchangers, typically welded plate units on catalytic reformers, whereas there are typically 400 -500 shell and tube units in a refinery.

3.3.1.8 General Heating/Cooling

Plate and frame heat exchangers are often used to exchange heat between treated cycle water and river, or sea, water as process cooling.

In addition, the use of compact heat exchanger designs in cogeneration and district heating/cooling systems is becoming a significant market.

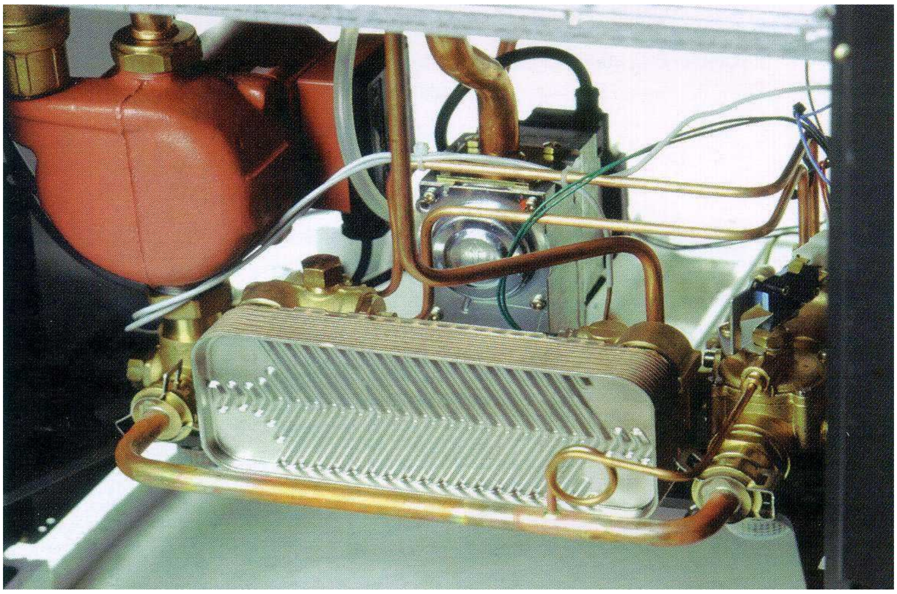

Figure 3.3.2 – Brazed Plate Heat Exchanger Heating Tap Water in a Combi Gas Boiler (Courtesy of APV)

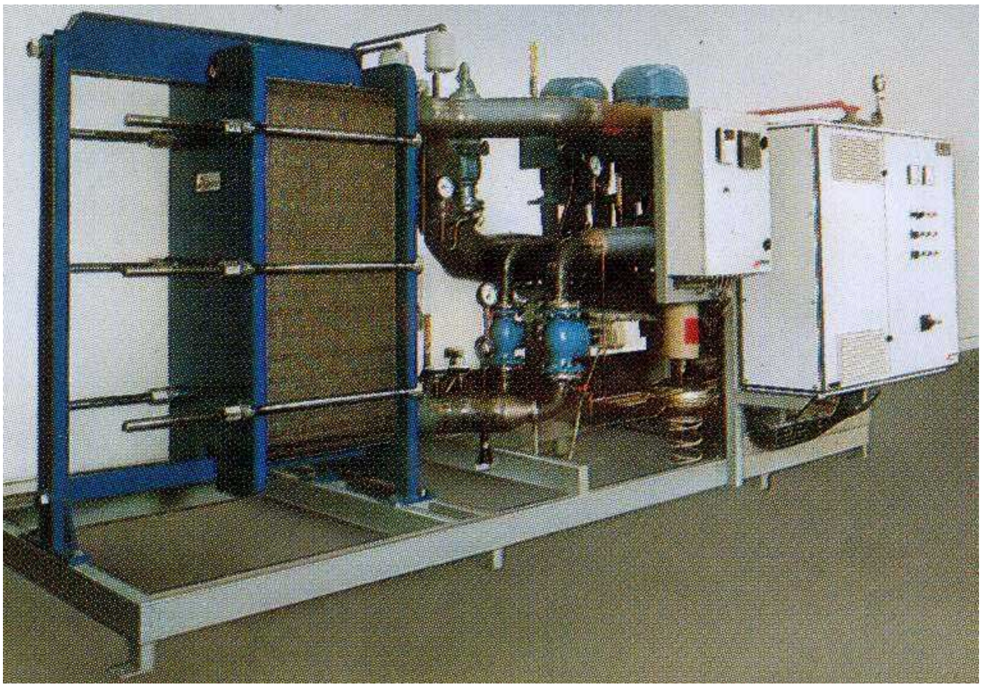

Figure 3.3.3 – Plate and Frame Exchanger in a 10 MW Heat Distribution Substation (Courtesy of APV)

3.3.2 Technical Applications

There are several generic applications for compact heat exchangers in the process industries.

3.3.2.1 Distillation

Plate-fin heat exchangers are routinely used in cryogenic separations, for example as reboilers in air separation processes. However, the application of compact heat exchangers as condensers/reboilers in large distillation plant is not yet developed, although the technology is likely to become appropriate as column sizes are reduced.

Plate heat exchangers can usefully be applied to solvent recovery, provided care is taken at the design stage to minimise fouling. Port strainers can, for example, be used to reduce the risk of clogging, and equipment suppliers recommend chlorination to prevent biological growth. Some manufacturers supply cleaning-in-place (CIP) systems and recommend cleaning intervals appropriate to each heat exchanger duty.

3.3.2.2 Evaporators

Intermediate (less compact) compact heat exchangers have proved effective on multiple-effect evaporators in corrosive environments, while plate heat exchangers are now recommended for mechanical vapour recompression (MVR) units. The number of MVR units used for effluent concentration is predicted to increase as disposal costs rise, and the plate and frame exchangers offer a number of advantages as they can combine pre-heating with evaporation in a single frame, and some variants can handle high levels of solids.

Figure 3.3.4 – Plate and Frame Evaporator/Condenser Installation
(Courtesy of APV)

3.3.2.3 Reactor Feed/Effluent Heaters

Welded plate heat exchangers are already used to cool reactor products, and are regularly used in catalytic reforming plant where they pre-heat the feed to the furnace while cooling the final reactor product.

For example, a welded plate heat exchanger installed as a steam heater on the glycol loop of a batch reactor has successfully handled a cyclic duty. Temperature differences of up to 150^{o}C occur between the glycol loop and the steam side, and there has been no indication of any fatigue-related problems.

Other types of heat exchanger can also be used to heat the reactor feed.

An example involves using a plate and shell heat exchanger to heat the mixed aromatic feed to a benzene-toluene-xylene (BTX) plant at a refinery. In the original installation, traces of olefins in the feed became thermally degraded to form polymers, and these continually fouled and blocked the traditional shell and tube heat exchangers used. Switching to longitudinal fin-tube designs gave rise to a small improvement, but polymer fouling still necessitated tube bundle replacement every six months.

Although conventional plate and frame exchangers were inappropriate because of the high processing temperatures and pressures, a plate and shell heat exchanger offered the same benefits under the more severe process conditions. The short residence time, in particular, gives less opportunity for polymerisation reactions to occur, while the higher turbulence reduces fouling. After installation, the following benefits were found:

- The plate and shell units operated continuously without significant fouling.
- The elimination of large pressure drops and low heat transfer rates, combined with improved reliability, reduced 'bottlenecks' within the unit by 25%.
- Tube bundle replacement is no longer required. Furthermore, in the event of irreversible fouling of the plate and shell heat exchanger, replacement costs would be lower.

3.3.2.4 Separation of Hazardous Streams

Where one or more hazardous process streams pass through a heat exchanger (particularly in the chemicals sector, but also offshore, in boiler plant and in certain refrigeration applications), process engineers need to provide added protection against cross-contamination.

Normally, using two heat exchangers to separate the fluids would be unattractive because of the significantly increased temperature difference. However, taking advantage of the close approach temperatures that are possible with most compact heat exchangers, can largely alleviate the problem.

In boiler plant, especially where a condensing economiser or spray recuperator (direct contact heat exchanger) is used, the mildly acidic condensate may best be cooled by passing it through a stainless steel plate heat exchanger.

Refrigeration and heat pumping can also benefit from this approach, and examples exist where hot acid has been used as a heat source for pre-heating boiler feed water, with two plate heat exchangers linking the source and sink via a separate liquid loop incorporating a pH alarm.

3.3.2.5 Air and Other Gas Compressors

More than 90% of the energy from air compressors is wasted in heating the motor, oil and the cooling system. Brazed plate heat exchangers, offered as an option by some compressor suppliers, can provide heat from water-cooled compressors for local process duties at temperatures of up to 40^{o}C.

Multi-stage gas compressors are major power users in several industrial sectors and dominate energy use in the production of liquefied gases. The power consumption and hence the overall compressor efficiency of such units are affected by the temperature approach and pressure drop of the intercoolers. There is therefore a strong incentive to reduce both parameters on multi-MW compressors, and compact heat exchangers can make a significant contribution in this respect. Various large gas compressors now employ compact heat exchangers as intercoolers.

Plate-fin heat exchangers used as compressor intercoolers and aftercoolers exhibited a 1^{o}C temperature difference between gas and coolant, and a lower pressure drop than conventional intercoolers. The resulting power saving is about 2.2%.

3.3.2.6 Corrosive Fluids at High Pressure

Compact titanium heat exchangers are available which are made by superplastic forming and diffusion bonding. This type of heat exchanger is potentially very attractive in the high-corrosion and high-pressure environments of offshore industries.

3.3.2.7 Refrigeration Equipment

The use of compact heat exchangers as evaporators and/or condensers can improve the cycle efficiency, reflected in the Coefficient of Performance (COP), of both vapour compression cycle refrigeration/chiller plant and heat pumps. Where the fluid to be chilled or heated is clean, brazed plate heat exchangers are normally used.

Many of the absorption cycle units under development in Europe and elsewhere, e.g. for producing cooling using prime mover exhaust heat, use plate or plate-fin heat exchangers. The result is a reduction in both size and capital cost, as well as higher COPs.

3.3.2.8 Mechanical Vapour Recompression (MVR)

The open cycle heat pump, or MVR unit, has found application in the chemicals and food and drink sectors, and in effluent concentration. A compact MVR evaporator capable of evaporating between 200 and 500 kg/hour water has been developed using plate heat exchangers as the feed pre-heater and evaporator.

3.3.2.9 Improving the Efficiency of Prime Movers

Prime movers are large pumps or compressors, and there is a growing demand for their improved efficiency, partly out of concern for the environment. Compact heat exchangers have an important role to play, both in heat recovery for external uses (e.g. steam raising, process water heating) and in increasing thermodynamic cycle efficiencies (e.g. recuperated gas turbines).

Plate heat exchangers and compact shell and tube heat exchangers are used routinely on reciprocating prime movers. Shell and tube units are used in exhaust gas heat recovery as well as in oil and water cooling, while plate exchangers are used for fuel and oil cooling. Cogeneration units routinely use plate heat exchangers for heat recovery from water and oil circuits. Brazed plate heat exchangers may be used for fuel duties with radiator water being commonly used as the heat sink.

A brazed plate heat exchanger of 120 kW cooling duty weighs 20 kg. This compares with 130 kg for an equivalent shell and tube heat exchanger.

Compact heat exchangers, either plate-fin exchangers or compact shell and tube units are routinely used in the fuel systems of aircraft gas turbines.

Compact gas turbine recuperators for cogeneration units of 250 to 500 kWe would have a volume of 0.2 to 0.3 m^3, up to a hundred-times less than equivalent conventional tubular heat exchangers.

3.3.3 Summary

It is clear that compact heat exchangers are widely used in a number of different industrial sectors. Furthermore, developments are under way that will increase the range of applications in the future. Table 3.3.3 summarises the situation to date.

Sector/Application	Type of Heat Exchanger
Chemicals and Petrochemicals	Plate and frame heat exchanger Brazed plate heat exchanger Welded plate heat exchanger Spiral heat exchanger Plate-fin heat exchanger Printed circuit heat exchanger Compact shell and tube heat exchanger Compact types retaining a shell
Cryogenics	Plate-fin heat exchanger Printed circuit heat exchanger
Food and drink	Plate and frame heat exchanger Brazed plate heat exchanger Welded plate heat exchanger Compact types retaining a shell Spiral heat exchanger
Paper and board	Plate and frame heat exchanger Spiral heat exchanger
Textiles and fabric care	Plate and frame heat exchanger
District Heating/Cooling	Plate and frame heat exchanger Brazed plate heat exchanger Plate-fin heat exchanger
Oil and gas processing	Plate and frame heat exchanger Brazed plate heat exchanger Welded plate heat exchanger Plate-fin heat exchanger Printed circuit heat exchanger
Prime movers	Plate and frame heat exchanger Brazed plate heat exchanger Plate-fin heat exchanger Compact shell and tube heat exchanger
Refrigeration	Plate and frame heat exchanger Brazed plate heat exchanger Plate-fin heat exchanger Printed circuit heat exchanger
Air compressors	Plate and frame heat exchanger Brazed plate heat exchanger
Mechanical vapour recompression	Plate and frame heat exchanger Brazed plate heat exchanger

Table 3.3.3 - Types of Compact Heat Exchanger Typically Used in Each Process Industry Sector

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.4

ENERGY EFFICIENCY AND HEAT EXCHANGE

This module discusses the relationship between energy conservation and heat exchanger selection emphasising the advantages of using compact heat exchanger designs. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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3.4.3 Integrated Pollution Prevention and Control

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ENERGY EFFICIENCY AND HEAT EXCHANGE

3.4.1 Introduction

Heat exchange is one of the fundamental principles of chemical and manufacturing engineering as well as being one of the key processes underpinning civilised life; an example of this being refrigeration units. Heat exchangers are ubiquitous throughout the industrial, domestic and transport sectors. The energy handled by exchangers either directly or indirectly is nationally significant as well as being of economic importance for process operators and suppliers.

Annual energy savings through the more widespread use of compact heat exchanger designs have been estimated as 8 Petajoules nationally. This is equivalent to around £20 million at 1996 prices.

If using compact heat exchangers leads to closer approach temperatures or reduced pressure drop, then energy savings will result.

3.4.2 Greenhouse Gas Reduction

Carbon dioxide emissions from the energy supply industry and from business are substantial fractions of the UK's greenhouse gas release inventory. In 1990 (baseline year) the energy supply industry contributed 37.5% of national carbon dioxide emissions and business (including the manufacturing and commercial sectors) contributed 40.5%.

Under the Kyoto Protocol agreed in 1997, there is a global commitment to reducing emissions of a basket of six greenhouse gases. The UK Government is committed to reducing our emissions to 12.5% below 1990 levels over the period 2008-2012. Furthermore, the Government have a manifesto objective of achieving a 20% reduction of carbon dioxide emissions by 2010 whilst maintaining UK competitiveness and promoting social inclusion.

To provide a greater financial incentive to save energy, the Government proposes to introduce a Climate Change Levy on all non-domestic users from 2001. This will be collected through utility bills and be based on usage, possibly adding up to 20% to some energy bills. However, these measures will be fiscally neutral across business as a whole as a result of reductions in National Insurance contributions and the funding of energy efficiency programmes.

A complex range of incentives and awareness is proposed as a means of achieving our targets. Improving energy efficiency is a fundamental element of achieving these commitments.

3.4.3 Integrated Pollution Prevention and Control

Demonstrating energy efficiency will be mandatory for processes covered by the IPPC (Integrated Pollution Prevention and Control) regulations. It is likely that site specific permit conditions, based on lists of technologies and benchmarks of cost-effective energy efficiency, will be developed. Heat exchange will inevitably form part of permit conditions where appropriate.

Sector specific guidance notes are expected to be published discussing the benchmarks and improvements in energy efficiency that might be expected from processes in each sector.

Negotiated agreements for clearly defined groups of installations may be an alternative means of delivering the energy efficiency requirement.

3.4.4 General Energy Efficiency Aspects

The general view is that very substantial energy (and therefore cost) savings can still be achieved across the whole spectrum of heat transfer applications by the use of more efficient heat exchange.

These benefits can be achieved

- Directly by using more thermally effective exchangers.
- By modifying existing (tubular) heat exchangers using passive or active enhancement.
- Indirectly by reducing the physical size and mass of exchanger designs thereby reducing the quantity of fabrication effort, energy and materials required.
- Indirectly by reducing associated energy consumptions such as pumping or compression.
- By enabling more efficient waste heat recovery (process integration) and recuperation.
- Through process intensification and the use of reactor exchangers.

Selection of effective heat exchangers for appropriate new or refurbished applications is a key element of realising these benefits. Naturally, energy effectiveness is only one element of the exchanger selection process, but this should be a key consideration.

From the perspective of energy efficiency, the heat exchanger must be viewed as part of the process system rather than a stand-alone unit. For example, pressure drop across an exchanger will be significant in terms of pump selection and power consumption, or a refrigeration compressor may use significantly less power if a higher coefficient of performance (COP) is achieved.

3.4.4.1 Thermal Effectiveness

As the outlet temperature of the cold stream approaches the inlet temperature of the hot stream, the thermal effectiveness (E) of the exchanger increases. This is shown in Table 3.4.1. and described in detail in Module 3.1. The values shown are theoretical values for optimum conditions that may not be achieved in reality.

Heat Exchanger Technology	Minimum Approach Temperature ΔT^oC	Maximum Thermal Effectiveness (E)
Shell and Tube	5	0.9
Double Pipe	5	0.9
Plate and Frame	1	0.95
Brazed Plate	1	0.95
Welded Plate Types	1	0.95
Plate-Fin	0.1	0.98
Printed Circuit	0.1	0.98
Air Cooled	10	0.8
Spiral	0.1	0.98
Plate and Shell	0.1	0.98

Table 3.4.1 – Approach Temperatures and Thermal Effectiveness for Common Heat Exchanger Technologies (adapted from HTFS Website)

A shell and tube heat exchanger with an effectiveness of 0.75, heating a single phase fluid from 10°C with a hot source stream at 100°C, will give a cold stream outlet temperature of 77.5°C: that is, an approach temperature of 22.5°C.

A compact heat exchanger with an effectiveness of 0.95, used for the same application, would give a cold stream outlet temperature of 95.5°C: that is, an approach temperature of only 4.5°C.

An arrangement of less effective exchangers in series could provide high heat transfer areas, and the overall thermal effectiveness of the assembly could thus be made higher. For the above example, multiple shell and tubes units could be considered, but at a much higher cost and even then an approach temperature of 4.5°C may not be achieved.

However, the greater area/volume ratio and high heat transfer coefficients of compact heat exchangers give a high effectiveness with a much smaller overall volume.

An energy and cost-effective heat exchanger with a high thermal effectiveness can therefore be achieved with a compact design.

3.4.4.2 Enhancement

Whilst primarily used for enhancing the tubular heat exchanger designs, enhancement may be applicable to some compact designs. Enhancement is concerned with increasing the heat transfer coefficient using additional active or passive techniques.

Effective enhanced heat transfer will increase efficiency leading to energy conservation and reduced costs. Some techniques may increase power consumption, either directly, or due to increased flow resistance through the exchanger. A relative analysis must be made of these aspects with respect to the energy balance.

Active techniques consume energy to produce vibration, rotation, ultrasound, pulsing, electrostatic fields and similar effects that enhance heat transfer.

Passive techniques involve modification of heat transfer surfaces, hydraulic devices and use of additives to enhance heat transfer.

A more detailed description of enhancement techniques is given in Module 3.5.

3.4.4.3 Physical Size

Using the relatively smaller compact designs primarily has a cost implication. A smaller exchanger often has a reduced requirement for materials and fabrication effort, thereby consuming less manufacturing energy.

Following installation, most compact designs have efficiency benefits over larger designs derived from less thermal mass and lower hold-up inventories; for example compact exchanger designs tend to be easier to control with short residence times.

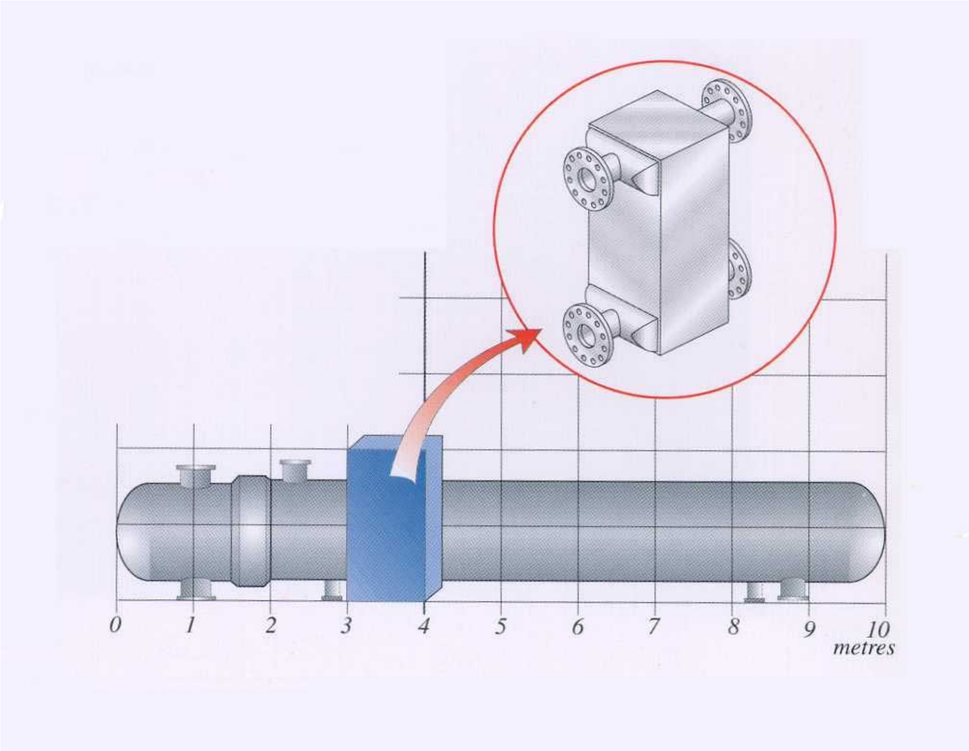

Figure 3.4.1 – Size Difference for Gas Cooling Heat Exchanger on a North Sea Platform (Courtesy of Rolls Laval Heat Exchangers Ltd)

3.4.4.4 Associated Energy Consumptions

For the reasons described above and elsewhere in this module, compact designs can have important net energy efficiency benefits, such as:

- For heat recovery applications, compact designs can recover more thermal energy from a combustion source flow, such as a gas turbine or co-generation engine exhaust, making more energy available for use elsewhere. Therefore a smaller combustion source is necessary for a given duty, or more thermal energy will be available from a fixed capacity combustion device.
- For systems involving inherent energy consumption, such as refrigeration, the heat transfer area can be reduced for a given compressor power, or an evaporator duty can be increased for a given compressor power, or the compressor power can be reduced for a given evaporator duty.
- For heat-actuated systems such as absorption refrigeration or conventional distillation, compact designs require less heat exchange surface area for a given duty.

3.4.5 Waste Heat Recovery

Waste heat recovery can be viewed as a true process, or more likely as being a more efficient application of unit processes. Either way the use of compact exchanger designs with closer approach temperatures can be important elements of heat recovery either directly or through mechanical vapour recompression or equivalent.

Waste heat is available in a number of low-temperature processes from generic sources including:

- Air compressors.
- Boilers.
- Prime movers, e.g. co-generation engines, gas turbines.
- Refrigeration plant.

Common sources of waste heat are described in Table 3.4.2 together with the nature of the heat carrier. ✔ denotes a potential heat exchange application.

Heat Source	Sector	Nature of Heat Source			
		Gas	Liquid	Vapour	Solid
Air compressors	All	✔	✔		
Boilers	All	✔	✔	✔	
Distillation	1,2		✔	✔	
Drying	All	✔		✔	✔
Dyeing and finishing	4	✔	✔		
Evaporation	1,2	✔	✔	✔	
Furnaces	1,2	✔	✔		✔
Gas Turbines	1,3	✔	✔		
Kilns	1,2	✔		✔	✔
Ovens	1,2	✔		✔	✔
Pasteurisers	2	✔	✔		
Process cooling	1,2	✔	✔	✔	✔
Process heating	All	✔	✔	✔	✔
Reciprocating engines	All	✔	✔		
Refrigeration	1,2	✔	✔	✔	
Spinning and weaving	4	✔			
Sterilisation	2	✔	✔	✔	
Ventilation	All	✔			
Washing	1,4		✔	✔	

Sectors where appropriate – 1 = Chemicals
2 = Food and drink
3 = Paper and board
4 = Textiles and fabric care

Table 3.4.2 – Potential Waste Heat Sources (adapted from Good Practice Guide 141)

It is beneficial to discuss the different types of waste heat exchanger, and their merits and limitations, although it should be understood that there is flexibility in this arrangement. For example, shell and tube exchangers are used in both liquid-liquid and gas-liquid applications.

3.4.5.1 Gas to Gas Heat Exchangers

This equipment class is perhaps the most competitive and prolific in terms of heat recovery. There are several different types of heat exchanger used for recovering heat from one gas stream and delivering it to another. The most common are the rotating regenerator, plate heat exchanger (not to be confused with its liquid-liquid counterpart), run-around coil, heat pipe or thermosyphon heat exchanger, and tubular recuperator. Only the plate heat exchanger is discussed here.

The gas-gas plate heat exchanger is generally the cheapest unit and is widely available for a range of process heat recovery applications. This recuperative heat exchanger is available in cross-flow (for compactness) or counter-flow (for efficiency) configurations. Commonly manufactured using aluminium plates, a typical 1 m^3 size unit handles 7 m^3/second. Plate heat exchangers are also manufactured in coated steel or stainless steel for corrosive duties or for higher temperatures.

Advantages include: wide availability; no cross-contamination; units are available in a range of materials; can be compact.

Limitations include: some variants can be difficult to clean; adjacent ducts are needed where the heat exchanger is located.

3.4.5.2 Liquid to Liquid Heat Exchangers

In many processes, liquid effluents are discharged well above ambient temperature, or process streams require heating or cooling before re-use. These afford opportunities for heat recovery using liquid-liquid heat exchangers. The two most common variants are shell and tube heat exchangers and plate units.

The shell and tube heat exchanger, described by some as the 'workhorse' of the process industries, dominates the heat exchanger market. It is also used extensively in refrigeration plant, as an evaporator or condenser. For straight tubes the fouling or corroding liquid should be arranged on the tube side. If fouling occurs on the shell side, a ‘U’ tube bundle may be used for ease of removal and external cleaning. However, no fouling liquid can be allowed on the tube side of ‘U’ tube bundles.

Advantages include: available in a wide range of sizes and materials; well established with design codes extensively developed; can be used for gas and/or two-phase duties.

Limitations include: can be bulky; not as efficient as some competing types.

Plate heat exchangers come in many forms, the most common being the stainless-steel gasketed variant, used extensively in the chemicals and food and drink sectors. Brazed and welded versions are available, permitting operation at higher pressures and temperatures, but access for cleaning is more difficult. The principal manufacturers are continuously extending the range of units available. Plate heat exchangers can be up to 95% efficient.

Advantages include: high efficiency; compact design; gasketed version can be extended for higher temperature and pressure duties and is readily stripped for cleaning; can be used for two-phase duties.

Limitations include: a restricted high-pressure capability; gasketed units can have a limited temperature range, determined by the gasket material.

Plate and shell heat exchangers are a relatively new development. These units combine the merits of shell and tube with those of plate heat exchangers. The compactness and high efficiency of a plate unit, configured to fit inside a shell, allows advantage to be taken of the higher operating pressures and temperatures afforded by the shell.

Advantages include: higher pressures than feasible with conventional plate units; higher temperature operation; retains access for cleaning on one side of the exchanger.

Limitations include: size range may be limited.

3.4.5.3 Gas or Vapour to Liquid Heat Exchangers

Gas, or vapour, to liquid exchangers are used where the requirement is for using a waste gas stream to heat a liquid. The most common type of gas to liquid heat exchangers is the economiser, normally associated with boiler plant, but equally applicable to thermal fluid heaters and other processes emitting hot gases. Economisers are available as condensing units recovering latent as well as sensible heat.

3.4.5.4 Heat Pumps and Mechanical Vapour Recompression Systems

There are few ways of upgrading waste heat which do not involve excessive energy input. However, heat pumps and mechanical vapour recompression (MVR) systems are two commercially available techniques that allow this to be done. These technologies are covered by other publications from the Energy Efficiency Best Practice Programme.

3.4.6 Process Intensification

Process intensification is a design philosophy for chemical plant that aims to achieve radical reductions in the size of the reaction plant and derive associated benefits.

Intensifying chemical manufacturing plant can lead to a number of major benefits:

- Improved energy efficiency.
- Improved safety.
- Improved reaction control.
- Waste minimisation: reduced raw material consumption and less by-product formation.
- Reduced capital cost.
- Reduced environmental impact.

Process intensification is a broad topic that covers many technical areas including heat exchangers, reactors, separators, utility plant and overall plant design.

The potential benefits of using compact integrated reactor heat exchangers (sometimes termed HEX reactors) are great, especially where exothermic reactions are involved.

Examples of potential benefits include:

- Reduced energy costs: high thermal effectiveness; close approach temperatures, more efficient heat transfer, less heat loss, elimination of mixing inefficiencies.
- Reduced capital cost: less material, simpler installation, smaller footprint and weight.
- Improved safety: smaller chemical inventory, better reaction control and rapid heat supply or removal.
- Increased throughputs: de-bottlenecking plants and increased cost-effectiveness of existing plants.
- Greater equipment flexibility: in the short term for rapid changes between small quantity, high value process runs, or in the medium term for rapid production response to changes in consumer demand.
- Higher purity products: equipment can be better optimised to reduce reaction by-products thereby minimising the need for downstream product processing, and unwanted by-product treatment and disposal.
- Waste minimisation: minimised reactor volume for cleaning or sanitisation, less raw material consumption and unwanted by-product production.

More detail on compact integrated reactor heat exchanger design is given in Module 3.7.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.5

HEAT TRANSFER ENHANCEMENT

This module presents general information on enhancing heat transfer. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description to exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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3.5.1 Introduction
3.5.2 Classification of Enhancement Techniques
3.5.3 Passive Enhancement Methods
3.5.4 Active Enhancement Methods

HEAT TRANSFER ENHANCEMENT

3.5.1 Introduction

Improving heat transfer performance is commonly referred to as heat transfer enhancement. Enhancement is normally concerned with increasing the heat transfer coefficient.

Thus, the product of enhancement techniques is to achieve any, or a combination of, the following:

- A reduction in the size of the heat exchanger for a given duty.
- An increase in the capacity of an existing heat exchanger.
- A reduction in the approach temperature difference.
- A reduction in pumping power.

Considerable synergy therefore exists between heat transfer enhancement, high thermal effectiveness and compact heat exchangers.

> Although many of the techniques used for heat transfer enhancement are primarily applicable to shell and tube designs, they are also used for compact heat exchangers. Plate surface modifications or the louvered fins in certain types of plate-fin heat exchangers, are two examples.

This section outlines the classification of enhancement techniques and lists the principal techniques according to Reay[1].

Enhanced heat transfer will increase efficiency leading to energy conservation and reduced costs. However, some techniques may increase power consumption, either directly, or due to increased flow resistance through the exchanger. A relative analysis must be made of these aspects.

This guide concentrates on the mainstream compact heat exchanger designs and is not concerned with the more specialised analysis of the enhancement techniques.

As active enhancement methods continue to be the subject of considerable research and development effort in the academic and industrial sectors, a synopsis of heat transfer enhancement techniques is presented based on information from Reay in 1991.

3.5.2 Classification of Enhancement Techniques

Enhancement techniques can be conveniently divided into two classes:

- Passive methods, such as extended surfaces, requiring no direct application of external power.
- Active techniques, such as rotation, consuming external power.

Compound enhancement, involving a combination of techniques, is also practised.

Future compact heat exchangers are expected to employ an increasing variety of enhancement techniques, complementing those already routinely used in some of the products described in Module 2.

3.5.3 Passive Enhancement Methods

Passive enhancement methods include:

- Treated surfaces (coatings and promoters).
- Rough surfaces.
- Extended surfaces.
- Displaced enhancement devices.
- Swirl flow devices.
- Surface tension devices.
- Porous structures.
- Additives (for gases and liquids).
- Coiled tubes.
- Surface catalysis.
- Grooves and rivulets.
- Chaotic convection.

3.5.4 Active Enhancement Methods

Active enhancement methods, which are less widely utilised, include:

- Mechanical aids.
- Surface vibration.
- Fluid vibration, including ultrasound.
- Electrostatic fields.
- Other electrical methods.
- Suction or injection.
- Jet impingement.
- Rotation.
- Induced flow instabilities e.g. pulses.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.6

SELECTION, SPECIFICATION AND OPERATION

This module presents the generic process advantages and limitations of compact heat exchanger designs. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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3.6.1 Introduction
3.6.2 The Specification Process
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SELECTION, SPECIFICATION AND OPERATION

3.6.1 Introduction

Compact heat exchangers will perform satisfactorily only if they are correctly specified, installed and operated. This module outlines the relevant factors to be considered when specifying compact heat exchangers, particularly where these differ from conventional models.

It examines the practical aspects of compact heat exchanger design, installation such as heat exchanger location and orientation, and considers issues of relevance to new and retrofit situations. Finally, because the operation of compact heat exchangers can have both benefits and drawbacks, it outlines precautions necessary to maximise the former and avoid the latter.

This module does not seek to duplicate the detailed specification procedures drawn up by individual companies or organisations such as the Compact Heat Exchanger Study Group. It does provide pointers based on the experience of both users and suppliers.

In addition software packages are available commercially or are used by equipment suppliers to design and cost compact heat exchanger applications (see module 3.8).

In most cases, the selection of a heat exchanger is closely associated with integration into a process flow stream. Designers should take into account the influence of the heat exchanger selection on energy efficiency and environmental impact in addition to considering the heat exchanger duty in isolation.

Table 3.6.1 gives a summary of compact heat exchanger characteristics. The data given here is to be used as a preliminary guide only for the selection of an appropriate compact heat exchanger. For detailed technology details, consult the equipment suppliers.

Table 3.6.1 - Comparative Summary of Compact Heat Exchanger Features

Type of Heat Exchanger	Area Density (m^2/m^3) (0)	Stream Types (1)	Materials (3)	Temperature Range (^oC)	Maximum Pressure (bar) (2)	Fluid Limitations	Cleaning Methods	Corrosion Resistance (18)	Multi-stream Capability	Multi-pass Capability
Plate and frame (Gasketed)	→200	liquid-liquid gas-liquid two-phase	s/s, Ti, Incoloy Hastelloy, graphite, polymer	-25 to +175 Special –35 to +200	Normal 25 Special 40	Limited by gasket type. Not normal for gases	Mechanical (14) Chemical	Good (7)	Yes (9)	Yes
Partially welded plate	→200	gas-liquid liquid-liquid two-phase	s/s, Ti, Incoloy Hastelloy	-35 to +200	25	Few - Some types need clean fluids	Mechanical (4, 14) Chemical (6)	Good (7)	No	Yes
Fully welded plate (AlfaRex)	→200	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Ni alloys	-50 to +350	40	Few - Some types need clean fluid	Chemical	Excellent	No	Yes
Brazed plate	→200	liquid-liquid two-phase	s/s	Cu braze –195 to +220 Ni braze →400	Cu braze 30 Ni braze 16	Must be compatible with braze	Chemical (5)	Good (8)	No	No (10)
Bavex plate	200 - 300	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ni, Cu, Ti, Special steels	-200 to +900	60	Few	Mechanical (11, 9) Chemical	Good	In principle	Yes
Platular plate	200	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Hastelloy, Ni alloys	-180 to +700	40	Few	Mechanical (12, 14)	Good	Yes (13)	Yes
Compabloc plate	→300	liquid-liquid two-phase	s/s, Ti, Incoloy	→300	32	Few	Mechanical (14)	Good	Not usually	Yes
Packinox Plate	→300	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, Hastelloy, Inconel	-200 to +700	300	Few	Mechanical (16, 14)	Good	Yes (9)	Yes
Spiral	→200	gas-liquid liquid-liquid two-phase	c/s, s/s, Ti, Incoloy, Hastelloy	→400 Special →850	30	Few	Mechanical (14)	Good	No	No

Type of Heat Exchanger	Area Density (m^2/m^3) (0)	Stream Types (1)	Materials (3)	Temperature Range (°C)	Maximum Pressure (bar) (2)	Fluid Limitations	Cleaning Methods	Corrosion Resistance (18)	Multi-stream Capability	Multi-pass Capability
Brazed plate-fin	800 – 1,500	gas-gas gas-liquid liquid-liquid two-phase	Al, s/s, Ti Ni alloy	Al –270 to +200 s/s cryogenic to +350	120	Low fouling Many limitations with Al	Chemical	Good	Yes	Yes
Diffusion-bonded plate-fin	700 - 800	gas-gas gas-liquid liquid-liquid two-phase	Ti, s/s, Ni	→400	200	Low fouling	Chemical	Excellent	Yes	Yes
Printed circuit	200 - 5,000	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ni, Ni alloys Ti	-200 to +900	500	Low fouling	Chemical	Excellent	Yes	Yes
Polymer - compact shell and tube	→275	liquid-liquid	Teflon	→200	11	Few	Water wash	Excellent	No	No
Plate and shell	→200	liquid-liquid	s/s, Ti, (shell also in c/s) (15)	-200 to +900	100	Few	Mechanical (16, 14) Chemical (17)	Good	No	Yes
Shell and tube (19)	→100	gas-gas gas-liquid liquid-liquid two-phase	s/s, Ti, (shell also in c/s), many different materials	-100 to +600	Shell 300 Tubes 1400	Few	Mechanical (16, 14) Chemical (17)	Good	No	Yes

Notes for Table 3.6.1 → = up to, s/s = stainless steel, Ti = titanium, Ni = nickel, Al = aluminium, Cu = copper, c/s= carbon steel

(0) Area includes the secondary surfaces (such as fins)
(1) Two-phase includes boiling and condensing duties
(2) The maximum pressure capability is unlikely to occur at the higher operating temperatures, and assumes no pressure/stress-related corrosion
(3) Other special alloys are frequently available
(4) On gasket side
(5) Ensure compatibility with copper braze
(6) On welded side
(7) Function of gasket as well as plate material
(8) Function of braze as well as plate material
(9) Not common
(10) Not in a single unit
(11) On tube side
(12) Only when flanged access provided, otherwise chemical cleaning
(13) Five fluids maximum
(14) Can be dismantled
(15) Shell may be composed of polymeric material
(16) On shell side
(17) On plate or tube side
(18) Primarily a function of construction materials rather than the exchanger type
(19) Not a compact exchanger technology (given for comparison)

3.6.2 The Specification Process

Practical selection of heat exchanger designs is a complex matter usually performed by a progressive series of actions including:

- Initial feasibility/selection of generic heat exchanger types based on the duty required including pressures, temperatures, characteristics of hot and cold process streams, previous experience, physical footprint etc. This eliminates unsuitable technologies at the first stage and feeds forward potential technologies to a more detailed feasibility assessment. Includes process integration aspects.

- Calculation of heat transfer areas including fouling characteristics for different exchanger configurations and different exchanger technologies.

- Comparative capital costing of heat exchanger options including different construction materials.

- Final selection including all the previous aspects plus installation costs, operational costs, energy efficiency, safety implications, maintenance requirement and other process specific selection criteria.

3.6.2.1 Initial Selection

The initial feasibility selection is a crucial step as experience shows that once a favoured technology is selected, then changes are unlikely to be made later. Consequently, it is important to ensure that compact heat exchanger designs are included in the initial technology selection (when appropriate).

> The objective of the initial selection and preliminary costing exercises is to identify options that can be submitted for detailed design evaluation and costing by suitable organisations.

The initial selection process takes account of a number of factors, all of which are related to the specific application (therefore no general rules can be given). These factors include the following:

- **Thermal and Hydraulic Requirements.**
  The amount of heat to be exchanged, the fluid inlet and outlet temperatures and the allowable pressure drop (or pumping power) are often specified as a result of overall process optimisation. Clearly, any selected heat exchanger must be capable of meeting this specification. Many heat exchangers are limited by a maximum operating temperature and pressure.

- **Compatibility with fluids and operating conditions.**
  The materials of construction of the selected exchanger must be able to contain the fluids on the respective sides without excessive corrosion. This is a particular concern where aluminium or gaskets are used. Wall thickness in some compact heat exchangers is less than in conventional shell and tube exchangers, so corrosion rates and allowances need careful assessment. Upstream corrosion products are more likely to block a compact heat exchanger than a conventional shell and tube exchanger. Small fluid passages in a compact heat exchanger can also corrode and become blocked. The exchanger must be capable of being designed and constructed to withstand the stresses due to fluid pressures and temperature differences (thermal stresses). Another consideration is the consequences of failure allowing the mixing or leakage.

- **Maintenance.**
  The characteristics of the process streams should be carefully considered to assess the requirements for cleaning (mechanical or chemical) and periodic replacement of all or part of the unit. Ease of modification could also be an important factor if process conditions are likely to change.

- **Availability.**
  Project time-scales will often dictate the use of standard designs, which can be delivered rapidly. There may also be limitations in the available design methods for some of the possible units. Sometimes multiple exchangers must be used in parallel to overcome size limitations.

- **Economic factors.**
  Obviously, if several possible heat exchanger types meet the physical requirements listed above, the final choice must be based on economics. For fixed pressure drop (pumping power), the main economic factor will be capital cost. However, it should be noted that there maybe a trade-off between pumping power and capital cost.

- **Space and weight.**
  In a number of applications the volume occupied by a heat exchanger is a vital consideration while in others, the weight is a crucial factor. In some applications, both volume and weight are important. Examples of such limitations are found in the aerospace industry where limitation of payload is economically and technically important and offshore structures where there is a large incentive to reduce the size and loading of platforms. Some compact exchangers can be mounted directly onto the top of distillation columns or similar. Exchangers should be suitably robust and capable of standing mechanical shock if necessary.

- **Fouling.**
  The potential for fouling with the respective fluids must be carefully assessed and the exchanger must be able to operate for the required period under the predicted conditions. The following points give general guidance:

  - Closed loops are unlikely to present significant fouling problems. Working fluids in refrigeration or power cycles, for example, should not cause any fouling in a well-engineered and maintained system.
  - Open loops are prone to fouling, and may require the installation of filters to remove particles, fibres etc., as well as chemical treatment to prevent biological growth, deposition of scale, or corrosion.
  - Once-through streams need to be examined on a case-by-case basis and appropriate action taken if the stream warrants it.
  - Spiral heat exchangers are particularly able to handle highly fouling liquids and slurries although other wide-gap designs are available.

Where fouling and/or corrosion are causes for concern, consider installing a closed cycle system as an intermediate loop between the heat source and the ultimate sink.

Where a closed cycle system is not an option, consult with the equipment supplier(s) and give detailed consideration to:

- Fouling margins.
- Optimal flow rates.
- Control of heat exchanger operation.
- Upstream fouling prevention.
- In-exchanger fouling control/removal.

For further information on dealing with the fouling issue, see Module 3.2.

- **Temperature and Pressure Cycling.**
  Continuous temperature and pressure cycling can induce stress-related failures in some exchanger designs. Also, vibration stress typical of some two-phase exchanges may also be a design consideration.

Further initial selection information for common heat exchanger designs is given in Table 3.6.2, or for other information, see Table 3.6.1.

Heat Exchanger Type	Maximum Pressure (bar)	Temperature Range (${}^{0}C$)	Fluid Limitations	Size Range for Single Unit (m^2)	Minimum ΔT (${}^{o}C$)	Maximum Thermal Effectiveness (E)
Air cooled	Process side 500	Process side ambient to +600	Few	5 to 350 (based on bare tube o/d.)	10	0.80
Brazed plate (copper braze)	30	-195 to +220	Must be compatible with braze	1 to 10	1	0.95
Double pipe	Shell 300 Tube 1400	-100 to +600	Few	0.25 to 200	5	0.90
Plate and shell	100	-200 to +900	Few	up to 500	0.1	0.98
Plate and frame	Normal 25 Special 40	-35 to +200	Limited by gasket type. Not normal for gases	1 to 2500	1	0.95
Brazed plate-fin	120	Al -269 to +204 s/s up to 650	Low fouling Many limits with Al	1 to 10000 (including fin area)	0.1	0.98
Printed circuit	500	-200 to +900	Low fouling	1 to 1000	0.1	0.98
Spiral	30	up to +400	Few	650	0.1	0.98
Shell and tube	Shell 300 Tube 1400	-100 to +600	Few	10 to 1000	5	0.90
Welded plate (Covers range of types)	Differential 30 to 60 Total with shell 300	Depends on type and material -200 to +650	Few Some types need clean fluids	1 to 10000 (type dependent)	1	0.95

Table 3.6.2 - Performance Summary of Some Heat Exchangers (adapted from HTFS Website)

With close approach temperatures in counter-current flow, exit temperatures can crossover; for example in spiral or plate-fin heat exchangers.

In principle, the initial selection process is usually independent of cost as this is determined in subsequent steps taking into account the heat transfer coefficient, materials of construction and other installation factors.

3.6.2.2 Preliminary Cost Estimation

The installed cost of a heat exchanger comprises the capital cost of the exchanger plus the installation cost (which may be substantial). Other factors may also be relevant such as operating cost.

Usually order of magnitude capital cost is used to compare different technology options modified as necessary by other impinging factors.

There are a variety of methods available to estimate cost for a given duty. ESDU publish standard methods determined by industry working groups that are summarised below and used in Module 4 design examples. Contact information is given in Module 5.2.

3.6.2.3 Detailed Design and Costing

This stage is usually performed by equipment suppliers' proprietary software according to criteria supplied by the client. As this stage tends to be costly, the number of potential technology variants should be minimised allowing the equipment supplier to optimise the exchanger design.

The following section is a plate heat exchanger design example illustrating a basic selection methodology.

3.6.2.4 Design Procedure for a Plate Heat Exchanger (adapted from an Alfa Laval Thermal Division example)

This example calculation illustrates the steps in the specification of a plate heat exchanger from fundamental equations. The derivation of the design includes empirical factors specific to this manufacturer's equipment.

<u>Hot Side Fluid</u>

60 kg/s of fluid A is to be cooled from 60°C to 40°C at a maximum pressure drop of 100 kPa. The properties at 50°C are:

Density	ρ	1050 kg/m^3
Heat Capacity	C_p	3.8 kJ/kg.K
Thermal Conductivity	λ	0.5 W/mK
Viscosity	μ	1.2 mPa.s

<u>Cold Side Fluid</u>

65 kg/s of water heated from 28°C to about 44.8°C at a maximum pressure drop of 100 kPa. The properties are:

Density	ρ	994.5 kg/m^3
Heat Capacity	C_p	4.18 kJ/kg.K
Thermal Conductivity	λ	0.622 W/mK
Viscosity	μ	0.74 mPa.s

<u>Design Procedure</u>

For definitions and values, see Tables 3.6.3 and Table 3.6.4.

Step 1 Calculate the Heat Load ($\dot{Q}$)

$$\dot{Q} = \dot{M}_1 Cp_1 dt_1 = \dot{M}_2 Cp_2 dt_2$$

$$\dot{Q} = 60 \times 3.8 \times 20$$

$$\dot{Q} = 4560\text{kW}$$

Step 2 **Calculate the Log Mean Temperature Difference (ΔT_m)**

$$\Delta T_m = \frac{\Delta t_1 - \Delta t_2}{\ln \frac{\Delta t_1}{\Delta t_2}}$$

$$\Delta T_m = \frac{15.2 - 12}{\ln \frac{15.2}{12}} = 13.54$$

Step 3 **Assume the Overall Heat Transfer Coefficient (U_o)**

Assume a value of 4000 $W/m^2.^oK$

Step 4 **Calculate the Area Required (A)**

$$\dot{Q} = U_o.A.\Delta T_m$$

Therefore; $$A = \frac{\dot{Q}}{U_0.\Delta T_m} = \frac{4.56 \times 10^6}{4000 \times 13.54} = 84.2 m^2$$

Step 5 **Select the Plate Heat Exchanger**

Using the mechanical data for the heat exchanger plate (see Table 3.6.4)

The area per plate; $A_{plate} = 0.96 m^2$

Therefore the number of plates required (N_{plates}) is; $\frac{84.2}{0.96} = 87.7 \approx 88$ plates

If we take 89 plates, this gives 44 channels for each fluid with an effective heat transfer area of $84.48 m^2$.

The required coefficient $$U_o = \frac{4.56 \times 10^6}{84.48 \times 13.54} W/m^2.^oK$$

therefore $$U_o = 3987 W/m^2.^oK$$

Step 6 Calculate Actual Overall Heat Transfer Coefficient (U_c)

The next step is to calculate the actual overall heat transfer coefficient under the operating conditions for the heat exchanger selected.

This is calculated from the equation:

$$\frac{1}{U_c} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{X_w}{\lambda_w}$$

Where α_1 = Hot Side Film Coefficient
α_2 = Cold Side Film Coefficient
X_w = Plate Thickness
λ_w = Thermal Conductivity of the Plate

The film coefficients are calculated from the dimensionless group, the Nusselt number (Nu). This in turn is calculated from the Reynolds (Re) and Prandtl (Pr) numbers, using the following relationship;

$$Nu = A.(Re)^B (Pr)^C$$

This relationship and the values of the constants A, B and C are derived for each plate heat exchanger model from experimental data.

Hot Side

The next step is to calculate the Reynolds Number (Re). The Reynolds number is related to the mass flux, which, in a complex 3-dimensional channel, is extremely complex to define.

Ideally the Reynolds number $Re = \dfrac{d_H \times \dot{M}}{\mu \times \text{cross sectional area}}$

However, in plate heat exchangers the Reynolds number is determined from the mass flow per channel, the viscosity, and a plate specific empirical channel constant C_{Re}:

So if $Re = \dfrac{C_{Re} \times \dot{M}}{\mu}$

and $C_{Re} = 3063.6$ (from Table 3.6.3)

and $\mu = 1.2$mPa.s

If no information is available, d_H is approximately 2 x plate spacing (in metres) and cross sectional area is approximately plate spacing x plate width.
then

$$\dot{M} = \frac{60}{44} = 1.36\text{kg/s.channel}$$

Note: The value of C_{Re} given in the manufacturer's data includes a factor of 1000, so that the viscosity can be entered in mPa.s.

Then;

$$Re = \frac{3063.6 \times 1.36}{1.2} = 3472$$

From Table 3.6.3 we can see that Re falls in the turbulent region, where the Reynolds-Nusselt-Prandtl relationship is as follows;

$$Nu = 0.14188 \times Re^{0.72} Pr^{0.37}$$

The next step is to calculate the Prandtl Number (Pr). If μ is entered in mPa.s then the heat capacity must be in kJ/kg°K;

$$Pr = \frac{Cp.\mu}{\lambda} = \frac{3800 \times 1.2 \times 10^{-3}}{0.5} = 9.12$$

Calculating the Nusselt Number (Nu);

$$Nu = 0.14188(3472)^{0.72}(9.12)^{0.37} = 113.85$$

$$Nu = \frac{\alpha.d_H}{\lambda}$$

Where; d_H = Hydraulic Diameter = 0.0068 m (from Table 3.6.4)

Therefore; $$\alpha = \frac{Nu.\lambda}{d_H} = \frac{113.85 \times 0.5}{0.0068} = 8371 W/m^2.^{o}K$$

Cold Side

Using the same method;

$$\mathrm{Re} = \frac{3063.6 \times 1.477}{0.74} = 6115$$

$$\mathrm{Pr} = \frac{4.18 \times 0.74}{0.622} = 4.97$$

$$\mathrm{Nu} = 0.14188(6115)^{0.72}(4.97)^{0.37} = 136.7$$

Therefore; $\alpha = \dfrac{136.7 \times 0.622}{0.0068} = 12504\,\mathrm{W/m^2.^\circ K}$

Wall Resistance

The resistance of the wall is X_w / λ_w

The plate thickness, $X_w = 0.6\mathrm{mm} = 0.0006\mathrm{m}$

The thermal conductivity, $\lambda_w = 16.85\,\mathrm{W/m^\circ K}$

Therefore, $\dfrac{X_w}{\lambda_w} = \dfrac{0.0006}{16.85} = 0.356 \times 10^{-4}\,\mathrm{m^2.^\circ K/W}$

So: Overall Heat Transfer Coefficient

$$\frac{1}{U_{calc}} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{X_w}{\lambda_w} = \frac{1}{8371} + \frac{1}{12504} + 0.356 \times 10^{-4} = 2.35 \times 10^{-4}\,\mathrm{m^2.^\circ K/W}$$

Therefore, $U_{calc} = 4255\,\mathrm{W/m^2.^\circ K}$

Step 7 **Is $U_{calc} > U_{overall}$?**

The calculated coefficient U_{calc} is of similar magnitude, but slightly higher than the required operating coefficient, so the estimate was correct.

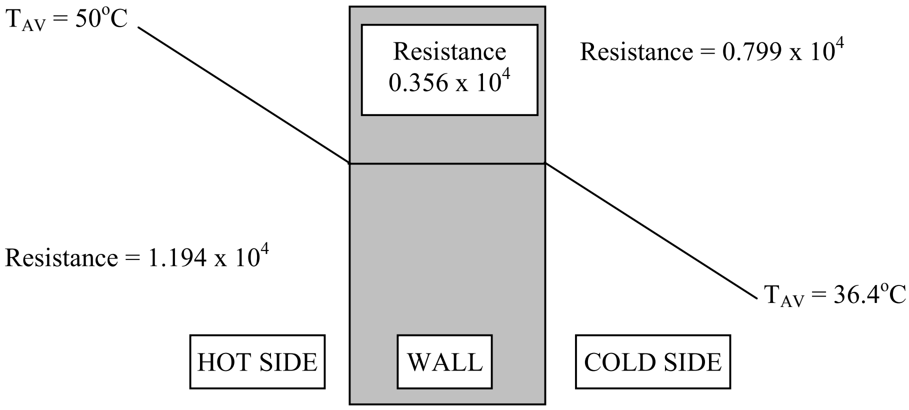
If U_{calc} is not the same, then the calculation should be repeated from step 3 with a different value of $U_{overall}$.

Step 8 Application of Correction Factors

(i) Wall Viscosity Correction

Step 6 assumes that the temperature, and thus the viscosity, are constant across the width of the channel. In reality the temperature at the wall is lower, and to compensate for this we use a wall viscosity correction factor.

The easiest way to estimate this is by calculating the wall temperature using the manufacturer's data from Table 3.6.3:



The total resistance = 2.35 x 10^4 m^2.°K/W

The total temperature drop ΔT_m = 13.6°C (from Step 2)

Therefore the temperature at the wall on the hot side is:

$$= 50 - \left(\frac{1.194}{2.35} \times 13.6\right) = 43.1^{\circ}\mathrm{C}$$

The viscosity of fluid A at 43.1°C = 1.4 mPa.s

From the Table 3.6.3 the wall viscosity correction factor is;

$$f_{IS} = \left(\frac{\mu}{\mu_w}\right)^{\frac{0.3}{(Re+1)^{0.125}}} = \left(\frac{1.2}{1.4}\right)^{0.1080} = 0.983$$

This should be applied to the film coefficient (α_1) as follows.

α_1 = 8371 x 0.983 = 8229 W/m^2.°K

Hence, the new value of the overall heat transfer coefficient is as follows;

$U_{calc} = 4218\ W/m^2.^oK$

For water the viscosity changes are small, so the viscosity effects are normally ignored.

(ii) Log Mean Temperature Difference Correction

In a plate heat exchanger the flow is distributed to a number of parallel channels. The channel at each end of the heat exchanger will be heated or cooled from one side only. The temperature progression in these channels will not be the same as in those channels exposed to heat transfer from both sides. This will naturally affect the overall temperature profile, with an increasing effect as the number of channels decreases.

To allow for this we apply a LMTD correction factor. To obtain a figure for this we need to calculate the temperature function F_θ.

$$F_\theta = \frac{U.A_{plate}}{\left[(\dot{M}.Cp)_1.(\dot{M}.Cp)_2\right]^{0.5}} = \frac{4.218 \times 0.96}{\left[(1.36 \times 3.8) \times (1.48 \times 4.18)\right]^{0.5}} = 0.716$$

From the empirical relationship of F_θ against F_T (LMTD correction factor) given in Figure 3.6.1, for $N_{plates} = 89$ and $n_s = 1$;

$F_T = 0.99$

Therefore, this correction factor can be reasonably ignored.

For the majority of plate-heat exchanger cases F_T is close to 1 and can be ignored.

Step 9 Calculate Design Margin

The true over-design margin is calculated as follows:

$$\text{Margin} = \frac{U_{calc} - U_{overall}}{U_{overall}} \times 100 = \frac{4218 - 3987}{3987} \times 100 = 5.8\%$$

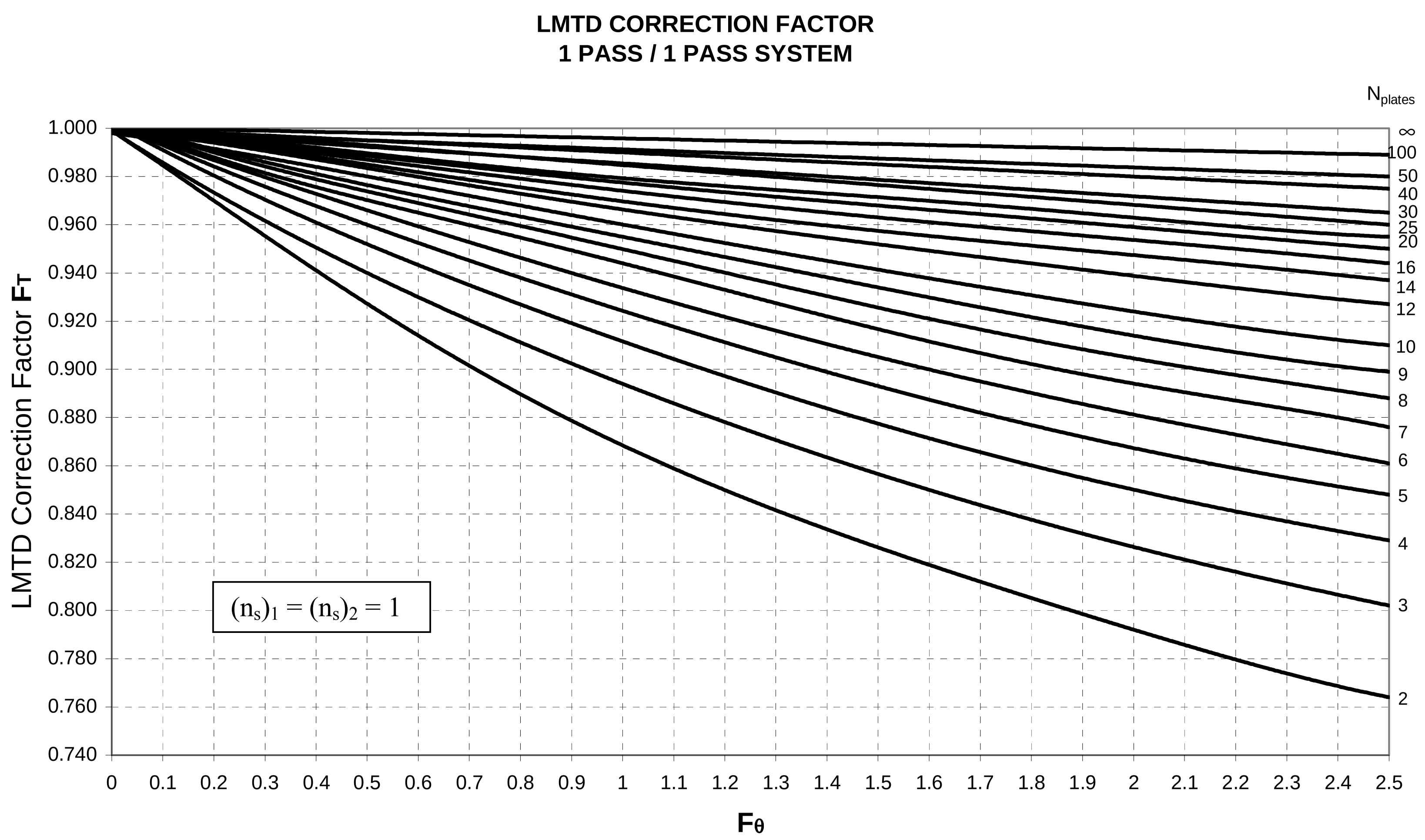


Figure 3.6.1 – Log Mean Temperature Correction Factor Relationship (Courtesy Alfa Laval Thermal Division)

Step 10 **Calculate Pressure Drop (Δp)**

Pressure drop $\Delta p = \Delta p_{is}\varphi_{is}\varphi_p$ where Δp_{is} is adjusted by viscosity and pressure corrections if significant.

As both fluids pass through the same number of channels, the higher pressure drop will be on the cold side.

$$\Delta p_{is} = 4f\left(\frac{1}{d_H}\right)\left(\frac{\rho u^2}{2}\right)$$

For a particular plate heat exchanger model, this can be simplified to;

$$\Delta p_{is} = f_{p(Re)}\left(\frac{\dot{M}^2}{\rho}\right)$$

Where $f_{p(Re)}$ is a friction factor, which is a function of the Reynolds Number.

Correlations of $f_{p(Re)}$ against Re have been derived experimentally and are given in Table 3.6.3. From Step 6 the cold side Reynolds number $Re = 6115$

Therefore $f_{p(Re)} = 0.0892 \times 10^6 Re^{-0.1} = 37277$

and $\Delta P_{is} = 37277 \times \dfrac{\left(\frac{65}{44}\right)^2}{994.5} = 81.8\text{kPa}$

In reality, the pressure drop in the connections should also be added.

Step 11 **Pressure Drop Corrections**

As $\Delta p = \Delta p_{is}\varphi_{is}\varphi_p$, then the viscosity and plate compression correction factors φ_{is} and φ_p must be estimated.

(i) ***Wall Viscosity Correction***

$$\text{On cold side temperature} = \frac{36.4 + (0.799 \times 13.6)}{2.35} = 41^{\circ}\mathrm{C}$$

Where

μ bulk water at 36.4°C = 0.70 mPa.s

and μ wall water at 41.0°C = 0.64 mPa.s

$$\text{Then if } \varphi_{is} = \left(\mu / \mu_w \right)^{\frac{-1}{(\mathrm{Re}+1)^{0.5}}}$$

$$= \left[\frac{0.70}{0.64} \right]^{0.0128}$$

$$= 1.001$$

Therefore φ_{is} can reasonably be ignored.

(ii) ***Plate Compression Correction Factor***

$$\varphi_p = \frac{(\varphi_p)_{\text{underpressureside}}}{(\varphi_p)_{\text{overpressureside}}}$$

From Table 3.6.4

$$\varphi_p = \frac{1.05}{0.95}$$

$$\varphi_p = 1.1$$

Therefore φ_p can reasonably be ignored.

Therefore in this example $\Delta p = \Delta p_{is}$

Step 12 Thermal Length

The 'thermal length' or 'θ-Value' is a dimensionless function, which can be derived from the two basic heat transfer equations;

$$\dot{Q} = U.A.\Delta T_m$$

$$\dot{Q} = \left(\dot{M}.Cp.dt\right)_1 = \left(\dot{M}.Cp.dt\right)_2$$

These can be arranged in the form;

$$\frac{U.A}{(\dot{M}.Cp)_1} = \frac{dt_1}{\Delta T_m} \quad \text{or} \quad \frac{U.A}{(\dot{M}.Cp)_2} = \frac{dt_2}{\Delta T_m}$$

The left-hand side of the equation represents a quantity which the heat exchanger is capable of, while the right-hand side represents the quantity that is required. These are always equal.

The quantity is known as the thermal length.

The thermal length or θ-value can be used in an alternative method to select the type of unit required. The θ-value for the required duty is compared with that of the viable heat exchangers. If the θ-value of the required duty exceeds a heat exchanger's achievable θ-value, it is necessary to use a multi-pass arrangement.

The design method for this type of arrangement is the same as for a single pass unit. However, the Log Mean Temperature Difference correction factor has a bigger effect, as some plates have the two fluids flowing co-currently on either side.

Step 13 Fouling

If fouling is known to be a significant factor, excess plate area may be required. For estimation see section 3.2.3.1

$a = 0.96$ $b = 0.653$ $c = 1.471$ $d_H = 0.0068$ $C_{Re} = 3063.6$

Heat Transfer	Pressure Drop
General	General
Laminar: $Re < 8$ $Nu = 0.51008\,Re^{0.333}\,Pr^{0.370}$	Laminar: $Re < 28$ $F_P = 5.2196\times10^6\,Re^{-1.00}$
Trans I: $8 < Re < 115$ $Nu = 0.30541\,Re^{0.580}\,Pr^{0.370}$	Trans I: $28 < Re < 185$ $F_P = 1.3765\times10^6\,Re^{-0.60}$
Trans II: $115 < Re < 160$ $Nu = 0.68422\,Re^{0.410}\,Pr^{0.370}$	Trans II: $185 < Re < 430$ $F_P = 0.2214\times10^6\,Re^{-0.25}$
Turbulent: $Re > 160$ $Nu = 0.14188\,Re^{0.720}\,Pr^{0.370}$	Turbulent: $Re > 430$ $F_P = 0.0892\times10^6\,Re^{-0.10}$
$\alpha_{is} = \dfrac{Nu.\lambda}{d_M}\,W/m^2.{}^oK$	$\Delta p_{is} = F_P \dot{M}^2 \rho^{-1} kPa$
Wall Viscosity Corrections	Wall Viscosity Corrections
$f_{is} = \left(\mu/\mu_w\right)^{\frac{0.3}{(Re+1)^{0.125}}}$	$\varphi_{is} = \left(\mu/\mu_w\right)^{\frac{-1}{(Re+1)^{0.5}}}$
	$\varphi_p = \dfrac{1.05}{0.95}$ from data sheet
Summary	Summary
$\alpha = \alpha_{is} f_{is}$ (General)	$\Delta p = \Delta p_{is} \varphi_{is} \varphi_p$ (General)

Plate Resistance $((m^2.{}^oK)/W)x10^4$

AISI 316	0.6mm: 0.356
AISI 316	0.8mm: 0.475
Ti/TiPd	0.6mm: 0.259
Ti	0.8mm: 0.345
Inc 825	0.6mm: 0.442

Subscript Notation;

is = isothermal
p = pressure

Table 3.6.3 – Manufacturer's Plate Heat Exchanger Data Sheet

Alfa Laval
Uniting vital technologies

Mechanical Data Sheet

1	Plate Area (A_{plate})	m^2	0.960					
2	Port Diameter or Equivalent	m	0.200					
3	Channel Width (b)	m	0.655					
4	Reynolds Number Coefficient (C_{Re})	-	3060					
5	Channel Type	-	L		M		H	
6	Hydraulic Diameter (d_H)	m	0.0068		0.0068		0.0068	
7	Velocity coefficient (C_U)	m^{-2}	450		450		450	
8	Maximum number of channels when $n_s = 1$	-	230		300		470	
9	Maximum number of channels when $n_s > 1$	-	130		175		270	

	Channel Type		L		M		H	
10	Pressure Difference	bar	>1		>1		>1	
11	Correction Factor Over Pressure Side (ψ_p)	-	0.90		0.95		1.0	
12	Correction Factor Under Pressure Side (ψ_p)	-	1.10		1.05		1.0	

13	Inside Diameter	mm	0.200		
14	C_c – Values Straight Connection (In/Out)	-	0.0/0.0		
15	C_c – Values Elbow Connection (In/Out)	-			
16	C_c – Values Single Corner (In/Out)	-			
17	C_c – Values Double Corner (In/Out)	-			

18	Material	-	304/316		Ti/TiPd		Inc825
19	Plate Thickness (Xw)	mm	0.6	0.8	0.6	0.8	0.6
20	Wall Resistance	$10^4\ m^2.^oK/W$	0.31	0.42	0.26	0.34	0.44

Table 3.6.4 – Manufacturer's Mechanical Data Sheet

3.6.3 ESDU Cost Estimation Method

3.6.3.1 Selection Between Feasible Types

Having obtained from Table 3.6.1 (and other information) a list of feasible heat exchanger types for the particular application, the next step is to obtain an indication of the cost of the heat exchanger for each of these types. Clearly, this is the most important factor in the selection.

The method described is based on estimating the cost, C, per unit $\dot{Q}/\Delta T_m$ where $\dot{Q}$ is the heat load and ΔT_m the corrected temperature difference. In this method, it is assumed that single units are employed. However, in order to avoid inefficiencies due to temperature distribution in duties employing multi-pass exchangers, multiple exchangers in series are commonly employed. In that case, the cost estimate has to be made as the sum of the costs of the individual exchangers, taking account of the calculated inter-exchanger temperatures. In order to calculate $\dot{Q}/\Delta T_m$, two approaches may be taken, namely the so-called "F_T" and "effectiveness" methods.

These are described, respectively, in Sections 3.6.3.2 and 3.6.3.3. Section 3.6.3.4 gives further information on the C-value method and describes the data presented here.

3.6.3.2 The F_T Method

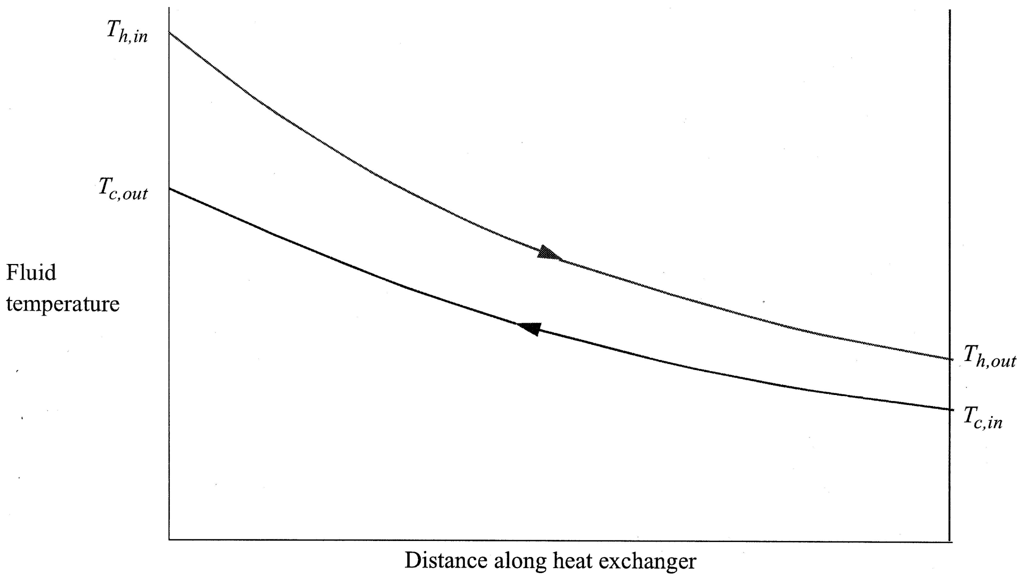


Figure 3.6.2 – Temperature Profiles in Counter-current Flow Heat Exchangers

For a pure counter-current heat exchanger, the temperatures vary with position as shown in Figure 3.6.2. For a constant overall heat transfer coefficient and for constant specific heat capacity of the fluid streams, the mean temperature difference ΔT_m is equal to the logarithmic mean temperature difference ΔT_{lm} given by:

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left[\dfrac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right]} \qquad (3.6.1)$$

Heat exchangers rarely have pure counter-current flow and a common practice is to correct the mean temperature difference by a factor that accounts for the deviation from pure counter-current operation:

$$\Delta T_m = F_T \Delta T_{lm} \qquad (3.6.2)$$

Information is available in the literature for the calculation of F_T. For quick calculations (often adequate at the level of accuracy of the method described here), the following approximate values of F_T, may be helpful.

Pure counter-current flow:	$F_T = 1.0$
Pure cross-flow exchangers:	$F_T = 0.7$
Multi-pass exchangers:	$F_T = 0.9$
Isothermal boiling and condensation:	$F_T = 1.0$

However, for any exchanger not having pure counter-current flow or having isothermal boiling or condensation, it is useful to check that the value of F_T is not so low as to be sensitive to small changes in stream temperature (typically F_T, should be greater than 0.8 for shell and tube exchangers). For these cases, therefore, it is worthwhile estimating F_T anyway.

The heat load for the exchanger is calculated from:

$$\dot{Q} = \dot{M}_h \left(h_{h,in} - h_{h,out}\right) = \dot{M}_c \left(h_{c,out} - h_{c,in}\right) \qquad (3.6.3)$$

For a single-phase flow with constant specific heat capacity, it follows that:

$$\dot{Q} = \dot{M}_h Cp_h \left(T_{h,in} - T_{h,out}\right) = \dot{M}_c Cp_c \left(T_{c,out} - T_{c,in}\right) \qquad (3.6.4)$$

where: Cp_h and Cp_c are the specific heat capacities of the hot and cold streams, respectively

and: $\dot{M}_h$ and $\dot{M}_c$ are the mass flowrates of the hot and cold streams, respectively.

It also follows that

$$\dot{Q} = UA\Delta T_m \tag{3.6.5}$$

where *A* is the heat exchanger surface and where U is referred to as the *overall heat transfer coefficient*. In practice, U is not constant along the heat exchanger. This is particularly so when phase change occurs and condensation or evaporation gives rise to a variation of velocity and local parameters along the heat exchanger. Similarly, the assumptions on which the calculation of ΔT_m is based are often violated. However, at the level of sophistication being used in the design selection process, it is sufficient for most purposes to assume "typical" values of U.

The procedure for determining $\dot{Q}/\Delta T_m$ using standard F_T charts is as follows.

- Calculate $R_k = [\dot{M}Cp]_h / [\dot{M}Cp]_c$ and calculate the parameter P from the expression:

$$P = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} \tag{3.6.6}$$

(note that $P = E$ if the cold stream has the smaller $\dot{M}Cp$).

- Read the value of F_T from the chart for the appropriate values of R_k and P.
- Calculate ΔT_{lm} from Equation (3.6.1).
- Calculate ΔT_m from Equation (3.6.2) and calculate $\dot{Q}/\Delta T_m$.

3.6.3.3 The Effectiveness Method

In general, the use of normal F_T charts needs an iterative solution if the outlet temperatures of the heat exchanger are not known. This led ESDU to prefer the effectiveness – N_{TU} approach. Furthermore the cited ESDU Data Items cover a much wider range of configurations than is available elsewhere in the literature (see volume 10 of the ESDU heat transfer series). Here, effectiveness E is defined as:

$$E = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{[T_{in} - T_{out}]_{larger}}{[T_{h,in} - T_{c,in}]} \tag{3.6.7}$$

where $\dot{Q}_{max}$ is the maximum heat transfer that can be achieved if the outlet temperature of one of the streams reaches the inlet temperature of the other stream. The number of transfer units N_{TU} is defined as:

$$N_{TU} = \frac{UA}{(\dot{M}.Cp)_{smaller}} \tag{3.6.8}$$

where $[\dot{M}Cp]_{smaller}$ is the lower product of the flow rate and the specific heat capacity of the two streams. The heat capacity ratio $C*$ is defined as:

$$C* = \frac{(\dot{M}Cp)_{smaller}}{(\dot{M}Cp)_{larger}} \tag{3.6.9}$$

From Equations (3.6.5) and (3.6.8)

$$\frac{\dot{Q}}{T_m} = [\dot{M}Cp]_{smaller} N_{TU} \tag{3.6.10}$$

The ESDU plots of E against N_{TU} are typified by the plot for a two-pass shell and tube heat exchanger given in Figure 3.6.3 and by that for an unmixed cross-flow exchanger given in Figure 3.6.4.

Notes:

(i) The subscripts "*larger*" and "*smaller*" refer to the magnitude of the terms and not to one or other of the streams.

(ii) The definitions of E, and *C* can* vary between sources and great care must be taken in transferring from one publication to another.

The procedure for using the effectiveness charts is as follows:

- Calculate C* from Equation (3.6.9) and E from Equation (3.6.7).
- Using the appropriate chart, read off N_{TU} for the calculated values of C* and E.
- Calculate the value of $\dot{Q}/\Delta T_m$ from Equation (3.6.10).

Alternatively ΔT_m, may be related directly to E and N_{TU} by the expression:

$$\Delta T_m = F_T \Delta T_{lm} = \Delta T_{lm} \ln[(1 - EC*)/(1 - E)]/[N_{TU}(1 - C*)] \tag{3.6.11}$$

Then $\dot{Q}/\Delta T_m$ is calculated by dividing the heat load by ΔT_m.

3.6.3.4 The C-value Method

The overall heat transfer coefficient, U, will vary with fluid enthalpy (particularly in multiphase systems) and with fluid velocity. There is a fundamental objection, therefore, to specifying a given value for a particular duty and configuration. Order-of-magnitude estimates can often be made for U to check for gross errors in heat exchanger size calculations.

Clearly, the heat transfer performance is related directly to the allowable pressure drop and the implication is that the latter must also follow conventional practice. Typical values of pressure drop are 1 per cent of inlet pressure for gases, 1 bar for liquids and 0.1 to 0.5 bar for condensers. Often, in the heat transfer textbooks, ranges of typical values are given. In the present section, single values are given as being typical of a particular duty and configuration.

There is no implication that the assigned value is particularly reliable as it is given merely for the purpose of quick order of magnitude assessment. This procedure is usually a precursor to detailed design. Where a very large range of conditions is covered in one unit, the unit can be considered as a series of connected units, each with its own representative conditions.

The values of U (and also, by inference, C) presented here are those for in-service conditions after fouling has taken place, allowing for the mitigating effect of cleaning.

If the appropriate value of U (including proper allowance for fouling) can be estimated approximately, then the heat exchanger area A may be calculated from:

$$A = \frac{1}{U}\left[\frac{\dot{Q}}{\Delta T_m}\right] \tag{3.6.12}$$

The quotient $\dot{Q}/\Delta T_m$ is characteristic of the heat exchanger duty being carried out and the cost of the exchanger to perform the duty is often estimated by multiplying *A* by a cost per unit area. A difficulty arises here over the definition of area, particularly when extended surfaces and complex geometries are employed.

However, from the point of view of the process designer, the important question is the overall cost for the particular duty, specified in terms of $\dot{Q}/\Delta T_m$. Here, a cost factor C is defined that represents the cost per unit $\dot{Q}/\Delta T_m$; C has the units £(W/K). For a particular duty and configuration, therefore, values of C may be estimated and are given in addition to U values in Tables 3.6.3 to 3.6.7. The cost of the heat exchanger may be estimated by simply multiplying C by $\dot{Q}/\Delta T$.

The cost of a heat exchanger per unit surface area, and hence the C value, decreases with increasing heat exchanger size. In the information presented here, C is given at specified values of $\dot{Q}/\Delta T$ and its value at intermediate values of $\dot{Q}/\Delta T$ may be estimated by logarithmic interpolation.

It should be noted that the cost values given do not normally include site installation. While the normal piping and fittings associated with a heat exchanger is often a relatively small item, this is not always true, particularly for hot gas applications, where ducting, perhaps refractory lined and, possibly, dampers capable of working at high temperatures are needed.

Often there is a relationship between installation cost and exchanger size and weight. This may affect the exchanger choice.

The costs are based on current costs in 1992. Costs will vary with time (approximately according to cost estimation indices for process plant) but the <u>relative</u> costs are likely to vary more slowly.

To summarise, the procedure for evaluation of the alternative feasible types of heat exchanger identified in the initial selection procedure is as follows.

- Estimate the heat load, $\dot{Q}$, from a heat balance (Equation (3.6.3)).

- If the F_T, method is being used, estimate the mean temperature difference, ΔT_m, using standard F_T charts together with the logarithmic mean temperature difference calculated from Equation (3.6.1). If the effectiveness method is being employed, calculate $\dot{Q}/\Delta T_m$ directly through Equation (3.6.7) to (3.6.10).

- Calculate the quotient $\dot{Q}/\Delta T_m$ for each proposed configuration (note that, for the particular duty required, the values of $\dot{Q}/\Delta T_m$ will vary between exchanger types since the temperature difference correction factor or N_{TU} value varies).

- From the tables provided for each exchanger type, read off the value of C, interpolating logarithmically between the levels of $\dot{Q}/\Delta T_m$ given in the tables.

- Calculate the cost of each configuration for the specified duty by multiplying $\dot{Q}/\Delta T_m$, by C and compare the costs, bearing in mind possible differences in installation and pumping costs.

- If one configuration is much cheaper than the others (by a factor of 1.5 to 2.0 or more, say) that design should be selected and detailed calculation and estimates carried out. If there are several designs at around the same cost, the performance of all of the designs should be estimated in greater detail.

Process industry experience shows that, particularly for the more conventional designs such as shell and tube exchangers and air-cooled heat exchangers, wide variations in quoted costs exist reflecting the suppliers current order position in addition to the standard costs of production. For tubular exchangers, the actual costs will also vary considerably with the configuration (type of shell, lengths of unit, tube diameter, *etc*., for shell and tube exchangers; number of tube rows, tube length, *etc*., for air cooled exchangers).

Tables of U and C values for various heat exchangers are given in Tables 3.6.5 to 3.6.10 as follows:

Table 3.6.5: Shell and tube heat exchangers
Table 3.6.6: Gasketed plate heat exchangers
Table 3.6.7: Printed circuit heat exchangers
Table 3.6.8: Plate-fin heat exchangers
Table 3.6.9: Welded plate heat exchangers
Table 3.6.10: Double pipe heat exchangers

It should be noted that the costs given in these tables are for the materials stated. The costs would differ if other materials were used.

3.6.4 Justifying Selections

Prepare a design proposal carefully. Innovative designs beyond tried and trusted technology may need cogent arguments for justification.

To ensure the most positive reception:

- Ensure that the appropriate information about compact heat exchangers is spread to decision-makers.
- Obtain details from likely equipment suppliers of successful installations elsewhere.

If there is a reluctance to install a compact heat exchanger on new plant, consider whether compact heat exchangers might be used to resolve a particular problem on an existing plant. Problems, such as fouling in the process fluids, are more likely to be well quantified on existing plant, making the benefits of a compact heat exchanger solution more immediately clear.

Be clear about the reason(s) for using a compact heat exchanger. If the main aim is size reduction, do not compromise this unnecessarily by also demanding an increase in thermal duty (although both may, of course, be possible).

Take into account all the costs associated with the new unit, including filters, special piping needs, etc., and present these costs clearly in the proposal. If an existing conventional heat exchanger is being replaced with a compact heat exchanger, new pipework will be needed. Furthermore, pre-treatment can be a significant part of the installation cost up to 10% typically.

Bear in mind the need for plant flexibility, and the possibility of plant expansion in the future.

3.6.5 Regulations

Heat exchanger manufacturers typically design to international pressure codes, such as BS 5500, Asme VIII, AD Merkblatter, Swedish Pressure Vessel Code, or Stoomvezen. The appropriate standards for the application should be defined during the design and specification activity as they will have cost implications.

3.6.6 Installation

If fouling is likely to reduce the run time of a compact heat exchanger, consider installing two identical units in parallel. If one becomes fouled, the flow can be diverted through the other. This principle is the same as incorporating a bypass on a waste heat recovery unit to permit cleaning or to avoid plant shutdown in the event of a failure.

Take extra care when installing, hydraulically testing and commissioning small passages to avoid fouling and possibly corrosion.

3.6.7 Operation and Maintenance

The list below gives some practical aspects of compact heat exchanger operation and maintenance that may have implications at the feasibility or design stage.

- **Check design limitations.** Be aware of the design limitations of the selected compact heat exchangers. Tight design criteria can limit operational flexibility, and optimum performance and minimum fouling will only be achieved when the unit is operated at, or near, its design conditions. Any reduction in, for instance, the velocity of a cooling water stream may increase fouling.

- **Give adequate training.** Make sure that staff are fully trained in compact heat exchanger operation. Failures have occurred where non-specialists in heat exchangers were unaware of operating practices and experience

- **Establish routine preventive maintenance.** Compact heat exchangers are more vulnerable to fouling or blockage than conventional shell and tube heat exchangers. Therefore, give the same high priority to the relevant preventive measures - filters, chemical dosing etc. - as to ensuring that equipment, such as the main pumps, remain serviceable.

- **Decide on procedures in case of failure or blockage.** If a failure occurs during operation, the general rule is to contact the manufacturer as soon as possible.

  Mechanical failure during operation may occur because liquids freeze or because of over-pressurisation, explosion, damage etc. If any of these occur, contact the manufacturer to discuss the possibilities of repair.

  Decide on contingency plans for dealing with a blocked compact heat exchanger, such as cleaning in situ, blocking off the affected layers of a plate-fin exchanger, or switching to standby/replacement units.

  The mechanical failure of one or more layers in a plate-fin, or similar type of compact heat exchanger, need not involve complete replacement. Layers - in some designs up to 10% of the layers may be blanked off to allow continued operation. However, you should consult your equipment supplier before proceeding in this way.

- **Identify overhaul procedures.** Some compact heat exchangers can be sent off-site to be overhauled. This is particularly beneficial in the case of gasketed plate heat exchangers, as the gaskets are refitted to the manufacturer's standards.

  If heat exchangers with gaskets are reassembled on site, ensure uniform gasket compression to minimise the risk of leaks. Use gaskets supplied by the heat exchanger manufacturer. With all re-assembly, it is important to ensure that the manufacturer's recommendations are followed.

#Table 3.6.5 - U and C Values for Shell and Tube Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1000	Low Pressure Gas(<1 bar)	U (W/m²K)	55	93	120	102	99	63	107	100	86
		C (£/(W/K))	5.70	5.02	5.51	4.93	4.96	5.50	4.87	4~95	5.11
	Medium pressure Gas(20 bar)	U (W/m²K)	93	300	350	429	375	120	530	388	240
		C (£/(W/K))	5.02	4.18	4.81	4.03	4.09	4.76	3.95	4.07	4.28
	High Pressure Gas(150 bar)	U (W/m²K)	120	350	400	600	450	200	600	400	300
		C (£/(W/K))	5.51	4.81	6.25	4.56	4.38	5.50	4.56	4.82	4.81
	Treated Cooling Water	U (W/m²K)	105	484	600	938	714	142	1607	764	345
		C (£/(W/K))	4.89	3.98	4.56	3.77	3.85	4.59	3.61	3.83	4.12
	Low Viscosity Organic Liquid	U (W/m²K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	4.96	4.09	4.38	3.91	3.97	4.67	3.81	3.95	4.20
	High Viscosity Liquid	U (W/m²K)	68	138	200	161	153	82	173	155	214
		C (£/(W/K))	5.39	4.61	5.50	4.46	4.51	5.16	4.42	4.50	4.33
	Boiling Water	U (W/m²K)	105	467	550	875	677	140	1432	722	336
		C (£/(W/K))	4.89	3.99	4.91	3.79	3.87	4.60	3.64	3.85	4.13
	Boiling Organic Liquid	U (W/m²K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	4.96	4.09	4.38	3.91	3.97	4.67	3.81	3.95	4.20
5000	Low Pressure Gas (<1 bar)	U (W/m²K)	55	93	120	102	99	63	107	100	86
		C (£/(W/K))	2.11	1.63	2.26	1.58	1.59	1.95	1.55	1.59	1.68
	Medium Pressure Gas(20 bar)	U (W/m²K)	93	300	350	429	375	120	530	388	240
		C (£/(W/K))	1.63	1.11	1.89	1.02	1.05	1.49	0.98	1.05	1.18
	High Pressure Gas(150 bar)	U (W/m²K)	120	350	400	600	450	200	600	400	300
		C (£/(W/K))	2.26	1.89	2.25	1.10	1.46	1.93	1.10	1.45	1.45
	Treated Cooling Water	U (W/m²K)	105	484	600	938	720	142	1607	764	345
		C (£/(W/K))	1.56	1.00	1.10	0.88	0.91	1.41	0.83	0.90	1.07
	Low Viscosity Organic Liquid	U (W/m²K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	1.59	1.05	1.46	0.95	0.99	1.46	0.89	0.98	1.13
	High Viscosity Liquid	U (W/m²K)	68	138	200	161	153	82	173	155	124
		C (£/(W/K))	1.86	1.43	1.93	1.36	1.38	1.71	1.32	1.37	1.48
	Boiling Water	U (W/m²K)	105	467	550	875	677	140	1432	722	336
		C (£/(W/K))	1.56	1.00	1.20	0.88	0.93	1.42	0.84	0.91	1.08
	Boiling Organic Liquid	U (W/m²K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	1.59	1.05	1.46	0.95	0.99	1.46	0.89	0.98	1.13

Table 3.6.5 - U and C Values for Shell and Tube Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
30000	Low Pressure Gas (<1 bar)	U (W/m^2K)	55	93	120	102	99	63	107	100	86
		C (£/(W/K))	1.11	0.76	1.06	0.73	0.74	0.99	0.71	0.73	0.80
	Medium Pressure Gas (20 bar)	U (W/m^2K)	93	300	350	500	375	120	530	388	240
		C (£/(W/K))	0.76	0.37	0.62	0.28	0.33	0.63	0.28	0.32	0.42
	High Pressure Gas (150 bar)	U (W/m^2K)	120	350	400	600	450	200	600	400	300
		C (£/(W/K))	1.06	0.62	0.94	0.40	0.53	0.73	0.40	0.62	0.62
	Treated Cooling Water	U (W/m^2K)	105	484	600	938	714	142	1607	764	345
		C (£/(W/K))	0.71	0.29	0.40	0.23	0.25	0.56	0.19	0.24	0.34
	Low Viscosity Organic Liquid	U (W/m^2K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	0.74	0.33	0.53	0.27	0.38	0.59	0.24	0.28	0.38
	High Viscosity Liquid	U (W/m^2K)	68	138	200	161	153	82	173	155	124
		C (£/(W/K))	0.94	0.57	0.73	0.52	0.53	0.83	0.50	0.53	0.60
	Boiling Water	U (W/m^2K)	105	467	550	875	677	140	1432	722	336
		C (£/(W/K))	0.71	0.29	0.49	0.23	0.25	0.56	0.20	0.25	0.35
	Boiling Organic Liquid	U (W/m^2K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	0.74	0.33	0.53	0.27	0.28	0.59	0.24	0.28	0.38
100000	Low Pressure Gas (<1 bar)	U (W/m^2K)	55	93	120	102	99	63	107	100	86
		C (£/(W/K))	0.95	0.58	0.93	0.54	0.55	0.83	0.52	0.55	0.62
	Medium Pressure Gas (20 bar)	U (W/m^2K)	93	300	350	429	375	120	530	388	240
		C (£/(W/K))	0.58	0.23	0.35	0.18	0.20	0.47	0.16	0.19	0.27
	High Pressure Gas (150 bar)	U (W/m^2K)	120	350	400	600	450	200	600	400	300
		C (£/(W/K))	0.93	0.35	0.58	0.24	0.28	0.64	0.24	0.32	0.39
	Treated Cooling Water	U (W/m^2K)	105	484	600	938	714	142	1607	764	345
		C (£/(W/K))	0.52	0.17	0.24	0.116	0.134	0.41	0.086	0.129	0.21
	Low Viscosity Organic Liquid	U (W/m^2K)	99	375	450	609	500	130	818	524	286
		C (£/(W/K))	0.55	0.20	0.28	0.145	0.162	0.44	0.125	0.158	0.24
	High Viscosity Liquid	U (W/m^2K)	68	138	200	161	153	82	173	155	124
		C (£/(W/K))	0.77	0.42	0.64	0.37	0.38	0.65	0.35	0.38	0.45
	Boiling Water	U (W/m^2K)	105	467	550	875	677	140	1432	722	336
		C (£/(W/K))	0.52	0.168	0.26	0.121	0.137	0.41	0.091	0.133	0.22
	Boiling Organic Liquid	U (W/m^2K)	99	375	450	600	500	130	818	524	286
		C (£/(W/K))	0.55	0.20	0.28	0.146	0.162	0.44	0.125	0.158	0.24

Table 3.6.5 - U and C Values for Shell and Tube Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1000000	Low Pressure Gas (<1 bar)	U (W/m^2K) C (£/(W/K))	55 0.93	93 0.55	120 0.93	102 0.50	99 0.52	63 0.81	107 0.48	100 0.51	86 0.60
	Medium pressure Gas(20bar)	U (W/m^2K) C (£/(W/K))	93 0.55	300 0.171	350 0.32	500 0.103	375 0.137	120 0.43	530 0.098	388 0.132	240 0.21
	High Pressure Gas (150 bar)	U (W/m^2K) C (£/(W/K))	120 0.93	350 0.32	400 0.58	600 0.19	450 0.25	200 0.56	600 0.19	400 0.28	300 0.37
	Treated Cooling Water	U (W/m^2K) C (£/(W/K))	105 0.49	484 0.106	600 0.19	938 0.058	714 0.074	142 0.36	1607 0.037	764 0.069	345 0.148
	Low Viscosity Organic Liquid	U (W/m^2K) C (£/(W/K))	99 0.52	375 0.137	450 0.25	600 0.087	500 0.103	130 0.39	818 0.065	524 0.099	286 0.179
	High Viscosity Liquid	U (W/m^2K) C (£/(W/K))	68 0.75	138 0.37	200 0.56	161 0.32	153 0.34	82 0.62	173 0.30	155 0.33	124 0.41
	Boiling Water	U (W/m^2K) C (£/(W/K))	105 0.49	467 0.11	550 0.20	875 0.061	677 0.077	140 0.37	1432 0.04	722 0.073	336 0.152
	Boiling Organic Liquid	U (W/m^2K) C (£/(W/K))	99 0.52	375 0.137	450 0.25	600 0.087	500 0.103	130 0.39	818 0.065	524 0.098	280 0.179

Note: The C values given in the above table are based on the assumption that the exchangers are constructed from carbon steel with a design pressure appropriate to the working pressure. The U-values take account of 'normal' fouling and are based on the outside surface area of the tubes. The costs are based on BEM designs with a minimum shell length to shell diameter ratio of 12. The maximum working pressure at which these approximate costs are valid is 20 bar, except for the cases where high-pressure gas is one of the fluids. Similarly, the maximum temperature at which these approximate costs are valid is 400°C. Further useful information on the effect of design parameters on costs is given by G.P. Purohit ("Estimating costs of shell and tube heat exchangers", *Chemical Engineering*, pp. 56-67, Aug. 22nd, 1983). Construction from stainless steel costs approximately 1.5 times more at pressures up to 30 bar and approximately 3 times more at a pressure of 150 bar.

Table 3.6.6 - U and C Values For Gasketed Plate Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Liquid	Parameter	Hot Side Liquid		
			Water	Aqueous Inorganic Liquid	Organic Liquid
5000	Water	U (W/m^2K) C (£/(W/K))	*5500* 0.160	3500 0.130 to 0.170	*1750* 0.140 to 0.190
	Aqueous Inorganic Liquid	U (W/m^2K) C (£/(W/K))	*3500* 0.130 to 0.170	*1750* 0.190	1250 0.160 to 0.210
	Organic Liquid	U (W/m^2K) C (£/(W/K))	*1750* 0.140 to 0.190	1250 0.160 to 0.210	1150 0.220
10000	Water	U (W/m^2K) C (£/(W/K))	5500 0.1	3500 0.1	1850 0.11
	Aqueous Inorganic Liquid	U (W/m^2K) C (£/(W/K))	3500 0.1	2200 0.1	1400 0.13
	Organic Liquid	U (W/m^2K) C (£/(W/K))	1850 0.11	1400 0.13	1150 0.15
50000	Water	U (W/m^2K) C (£/(W/K))	*5500* 0.025	3500 0.025 to 0.035	1850 0.035
	Aqueous Inorganic Liquid	U (W/m^2K) C (£/(W/K))	3500 0.025 to 0.035	3500 0.035	1400 *0.055*
	Organic Liquid	U (W/m^2K) C (£/(W/K))	1850 0.035	1400 *0.055*	1150 *0.065*
100000	Water	U (W/m^2K) C (£/(W/K))	*5500* 0.025	3500 0.035	1850 0.045
	Aqueous Inorganic Liquid	U (W/m^2K) C (£/(W/K))	3500 0.035	3500 0.035	1400 *0.055*
	Organic Liquid	U (W/m^2K) C (£/(W/K))	1850 0.045	1400 0.055	1150 0.065

Table 3.6.6 - U and C Values for Gasketed Plate Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Liquid	Parameter	Hot Side Liquid		
			Water	Aqueous Inorganic Liquid	Organic Liquid
500000	Water	U (W/m^2K) C (£/(W/K))	5500 0.015	3500 0.016	1850 0.020
	Aqueous Inorganic Liquid	U (W/m^2K) C (£/(W/K))	3500 0.016	3500 0.020	1400 0.035
	Organic Liquid	U (W/m^2K) C (£/(W/K))	1850 0.020	1400 0.035	1150 0.045
1000000	Water	U (W/m^2K) C (£/(W/K))	5500 0.015	3500 0.016	1850 0.025
20000000	Water	U (W/m^2K) C (£/(W/K))	5500 0.015	3500 0.016	1850 0.025

Notes:
1. Cost figures refer to stainless steel plates and operating pressures of 10 bar.
2. If titanium plate is used costs will be 1.7 to 2.0 times higher.
3. If pressure is increased to 25 bar costs will be 1.3 to 1.5 times higher

Table 3.6.7 - U and C Values for Printed Circuit Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	30 per cent Triethylene Glycol/Water	Condensing Hydrocarhon	Low Viscosity Liquid (<1 cP)	Medium Viscosity Liquid (1 to 5 cP)	High Viscosity Fluid (20 cP)	Condensing Steam
1000	Low Pressure Gas(<1 bar)	U (W/m²K) C (£/(W/K))	198 12	331 12	357 12	369 12	338 12	356 12	310 12	236 12	378 12
	Medium Pressure Gas (20bar)	U (W/m²K) C (£/(W/K))	331 12	1029 t2	1324 12	1506 12	1090 12	1304 12	845 12	458 12	1666 12
	High Pressure Gas (150 bar)	U (W/m²K) C (£/(W/K))	357 12	1324 12	1856 12	2234 12	1427 12	1816 12	1034 12	508 12	2605 12
	30 % Triethylene Glycol/Water	U (W/m²K) C (£/(W/K))	364 12	1506 12	2234 12	2804 12	1641 12	2176 12	1141 12	533 12	3414 12
	Boiling Organic Liquid	U (W/m²K) C (£/(W/K))	321 12	932 12	1168 12	1307 12	982 12	1152 12	778 12	438 12	1426 12
	Low Viscosity Liquid(<1 cP)	U (W/m²K) C (£/(W/K))	356 12	1304 12	t816 12	2176 12	1404 12	1778 t2	102t 12	505 12	2526 12
	Medium Viscosity Liquid (l - 5 cP)	U (W/m²K) C (£/(W/K))	3t0 12	845 12	1034 12	1141 12	886 12	1021 12	716 12	417 12	1231 12
	High Viscosity Liquid(2OcP)	U (W/m²K) C (£/(W/K))	236 12	458 12	508 12	533 12	470 12	505 12	417 12	294 12	552 12
	Treated Cooling Water	U (W/m²K) C (£/(W/K))	376 12	1621 12	2496 12	3230 12	1778 12	2424 12	1206 12	547 12	4068 12
5000	Low Pressure Gas(<1 bar)	U (W/m²K) C (£/(W/K))	198 5.2	331 3.6	357 4.0	369 3.6	338 3.6	356 3.6	310 3.6	236 4.8	378 3.6
	Medium Pressure Gas (20 bar)	U (W/m²K) C (£/(W/K))	331 3.6	1029 2.4	1324 2.8	1506 2.4	1090 2.4	1304 2.4	845 2.4	458 2.5	1666 2.4
	High Pressure Gas (150 bar)	U (W/m²K) C (£/(W/K))	357 4.0	1324 2.8	1856 3.2	2234 2.8	1427 2.8	1816 2.8	1034 2.8	508 2.8	2605 2.8
	30 % Triethylene Glycol/Water	U (W/m²K) C (£/(W/K))	369 3.6	1506 2.4	2234 2.8	2804 2.4	1641 2.4	2176 2.4	1141 2.4	533 2.4	3414 2.4
	Boiling Organic Liquid	U (W/m²K) C (£/(W/K))	321 3.6	932 2.4	1168 2.8	1307 2.4	982 2.4	1152 2.4	778 2.4	438 2.7	1426 2.4
	Low Viscosity Liquid (<1 cP)	U (W/m²K) C (£/(W/K))	356 3.6	1304 2.4	1816 2.8	2176 2.4	1404 2.4	1778 2.4	1021 2.4	505 2.4	2526 2.4
	Medium Viscosity Liquid (1 5 cP)	U (W/m²K) C (£/(W/K))	310 3.6	845 2.4	1034 2.8	1141 2.4	886 2.4	1021 2.4	716 2.4	417 2.7	1231 2.4
	High Viscosity Liquid (20 cP)	U (W/m²K) C (£/(W/K))	236 4.8	458 2.6	508 2.8	533 2.4	470 2.6	505 2.4	417 2.7	294 2.8	552 2.4
	Treated Cooling Water	U (W/m²K) C (£/(W/K))	376 3.6	1621 2.4	2496 2.8	3230 2.4	1778 2.4	2424 2.4	1206 2.4	547 2.4	4068 2.4

Table 3.6.7 - U and C Values for Printed Circuit Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	30 per cent Triethylene Glycol/Water	Condensing Hydrocarhon	Low Viscosity Liquid (<1 cP)	Medium Viscosity Liquid (1 to 5 cP)	High Viscosity Fluid (20 cP)	Condensing Steam
30000	Low Pressure Gas(<1 bar)	U (W/m^{2}K) C (£/(W/K))	198 2.57	331 1.76	357 2.58	369 1.62	338 1.71	356 1.66	310 1.82	236 2.22	378 1.59
	Medium Pressure Gas (20bar)	U (W/m^{2}K) C (£/(W/K))	331 1.76	1029 0.96	1324 0.87	1506 0.60	1090 0.92	1304 0.80	845 1.04	458 1.47	1666 0.60
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	357 2.58	1324 0.87	1856 0.73	2234 0.67	1427 0.87	1816 0.67	1034 1.26	508 2.01	2605 0.67
	30 % Triethylene Glycol/Water	U (W/m^{2}K) C (£/(W/K))	369 1.62	1506 0.60	2234 0.67	2804 0.43	1641 0.60	2176 0.60	1141 0.85	533 1.31	3414 0.40
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	321 1.78	932 0.99	1168 0.87	1307 0.80	982 0.96	1152 0.89	778 1.07	438 1.48	1426 0.80
	Low Viscosity Liquid (<1 cP)	U (W/m^{2}K) C (£/(W/K))	356 1.65	1304 0.80	1816 0.69	2176 0.60	1404 0.80	1778 0.60	1021 0.94	505 1.36	2526 0.60
	Medium Viscosity Liquid (1 - 5 cP)	U (W/m^{2}K) C (£/(W/K))	310 1.82	845 1.04	1034 1.26	1141 0.85	886 1.00	1021 0.93	716 1.11	417 1.53	1231 0.80
	High Viscosity Liquid (2O cP)	U (W/m^{2}K) C (£/(W/K))	236 2.22	458 1.47	508 2.01	533 1.31	470 1.42	505 1.36	417 1.53	294 1.94	552 1.29
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	376 1.59	1621 0.60	2496 0.67	3230 0.40	1778 0.60	2424 0.50	1206 0.80	547 1.29	4068 0.40
100000	Low Pressure Gas(<1 bar)	U (W/m^{2}K) C (£/(W/K))	198 2.10	331 1.40	357 2.20	369 1.24	338 1.34	356 1.28	310 1.45	236 1.84	378 1.22
	Medium pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	331 1.14	1029 0.59	1324 0.74	1506 0.44	1090 0.55	1304 0.49	845 0.66	458 1.09	1666 0.42
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	357 2.22	1324 0.74	1856 0.65	2234 0.30	1427 0.69	1816 0.57	1034 0.88	508 1.63	2605 0.45
	30 % Triethylene Glycol/Water	U (W/m^{2}K) C (£/(W/K))	369 1.24	1506 0.44	2234 0.50	2804 0.31	1641 0.41	2176 0.35	1141 0.52	533 0.94	3414 0.28
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	321 1.40	932 0.62	1168 0.80	1307 0.48	982 0.58	1152 0.52	778 0.69	438 1.11	1426 0.45
	Low Viscosity Liquid (<1 cP)	U (W/m^{2}K) C (£/(W/K))	356 1.28	1304 0.49	1816 0.57	2176 0.35	1404 0.46	1778 0.39	1021 0.57	505 0.98	2526 0.32
	Medium Viscosity Liquid (1-5 cP)	U (W/m^{2}K) C (£/(W/K))	310 1.45	845 0.66	1034 0.88	1141 0.52	886 0.63	1021 0.57	716 0.74	417 1.16	1231 0.50
	High Viscosity Liquid (20 cP)	U (W/m^{2}K) C (£/(W/K))	236 1.84	458 1.09	508 1.63	533 0.94	470 1.04	505 0.98	417 1.15	294 1.57	552 0.91
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	376 1.22	1621 0.42	2496 0.46	3230 0.30	1778 0.39	2424 0.33	1206 0.50	547 0.92	4068 0.24

Table 3.6.7 - U and C Values for Printed Circuit Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	30 per cent Triethylene Glycol/Water	Condensing Hydrocarhon	Low Viscosity Liquid (<1 cP)	Medium Viscosity Liquid (1 to 5 cP)	High Viscosity Fluid (20 cP)	Condensing Steam
300000	Low Pressure Gas(<1 bar)	U (W/m^{2}K)	198	331	357	369	338	356	310	236	378
		C (£/(W/K))	1.29	0.48	2.09	1.13	1.23	1.17	1.34	1.74	1.11
	Medium Pressure Gas (20bar)	U (W/m^{2}K)	331	1029	1324	1506	1090	1304	845	458	1666
		C (£/(W/K))	1.29	0.96	0.63	0.34	0.45	0.38	0.56	0.99	0.31
	High Pressure Gas (150 bar)	U (W/m^{2}K)	357	1324	1856	2234	1427	1816	1034	508	2605
		C (£/(W/K))	2.09	0.63	0.55	1.39	0.58	0.47	0.78	1.53	0.34
	30 % Triethylene Glycol/Water	U (W/m^{2}K)	369	1506	2234	2804	1641	2176	1141	533	3414
		C (£/(W/K))	1.13	0.34	0.39	0.20	0.31	0.24	0.42	0.83	0.17
	Boiling Organic Liquid	U (W/m^{2}K)	321	932	1168	1307	982	1152	778	438	1426
		C (£/(W/K))	1.30	0.51	0.70	0.37	0.48	0.41	0.59	1.00	0.34
	Low Viscosity Liquid(<1 cP)	U (W/m^{2}K)	356	1304	1816	2176	1404	1778	1021	505	2526
		C (£/(W/K))	1.17	0.38	0.47	0.24	0.35	0.29	0.46	0.88	0.22
	Medium Viscosity Liquid (1 - 5 cP)	U (W/m^{2}K)	310	845	1034	1141	886	1021	716	417	1231
		C (£/(W/K))	1.34	0.36	0.78	0.42	0.52	0.46	0.63	1.05	0.39
	High Viscosity Liquid (2O cP)	U (W/m^{2}K)	236	458	508	533	470	505	417	294	552
		C (£/(W/K))	1.74	0.99	1.53	0.83	0.94	0.88	1.05	1.46	0.81
	Treated Cooling Water	U (W/m^{2}K)	376	1621	2496	3230	1778	2424	1206	547	4068
		C (£/(W/K))	1.11	0.32	0.35	0.19	0.29	0.22	0.40	0.81	0.16
1000000	Low Pressure Gas (<1 bar)	U (W/m^{2}K)	198	331	357	369	338	356	310	236	378
		C (£/(W/K))	1.94	1.25	2.06	1.10	1.20	1.14	1.30	1.70	1.07
	Medium Pressure Gas (20 bar)	U (W/m^{2}K)	331	1029	1324	1506	1090	1304	845	458	1666
		C (£/(W/K))	1.25	0.44	0.59	0.30	0.41	0.34	0.52	0.95	0.27
	High Pressure Gas (150 bar)	U (W/m^{2}K)	357	1324	1856	2234	1427	1816	1034	508	2605
		C (£/(W/K))	2.06	0.59	0.51	0.35	0.54	0.43	0.74	1.49	0.30
	30 % Triethylene Glycol/Water	U (W/m^{2}K)	369	1506	2234	2804	1641	2176	1141	533	3414
		C (£/(W/K))	1.10	0.30	0.35	0.16	0.27	0.21	0.38	0.80	0.14
	Boiling Organic Liquid	U (W/m^{2}K)	321	932	1168	1307	982	1152	778	438	1426
		C (£/(W/K))	1.26	0.47	0.66	0.33	0.44	0.38	0.55	0.96	0.31
	Low Viscosity Liquid (<1 cP)	U (W/m^{2}K)	356	1304	1404	2176	1404	1778	1021	505	2526
		C (£/(W/K))	1.14	0.34	0.43	0.21	0.31	0.25	0.42	0.84	0.18
	Medium Viscosity Liquid (1-5 cP)	U (W/m^{2}K)	310	845	1034	1141	886	1021	716	417	1231
		C (£/(W/K))	1.30	0.52	0.74	0.38	0.49	0.42	0.60	1.01	0.35
	High Viscosity Liquid (20 cP)	U (W/m^{2}K)	236	458	508	533	470	505	417	294	552
		C (£/(W/K))	1.70	0.95	1.49	0.80	0.90	0.84	1.01	1.42	0.77
	Treated Cooling Water	U (W/m^{2}K)	376	1621	2496	2320	1778	2424	1206	547	4068
		C (£/(W/K))	1.08	0.28	0.32	0.14	0.25	0.19	0.36	0.78	0.12

Note: The above values were calculated on the basis of construction from Type 316L stainless steel.

Table 3.6.8 - U and C Values for Plate-Fin Heat Exchangers (Courtesy of ESDU)

(Key: NA - Not Applicable; NUS - Not Common)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
5000	Low Pressure Gas (<1 bar)	U (W/m²K) C (£/(W/K))	163 3.10	217 3.10	NA	NA	264 3.10	NUS	NUS	270 3.10	NUS
	Medium Pressure Gas (2O bar)	U (W/m²K) C (£/(W/K))	217 3.10	325 3.10	NA	NA	377 3.10	NUS	NUS	402 3.10	NUS
	High Pressure Gas (150 bar)	U (W/m²K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m²K) C (£/(W/K))	315 3.10	491 3.10	NA	NA	NUS	NUS	NUS	NUS	NUS
	Low Viscosity Hydrocarbon Liquid	U (W/m²K) C (£/(W/K))	NUS	NUS	NA	NA	NUS	NUS	NUS	NUS	NUS
	High Viscosity Hydrocarbon Liquid	U (W/m²K) C (£/(W/K))	NUS	NUS	NA	NUS	NUS	NUS	NUS	NUS	NUS
	Boiling Water	U (W/m²K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Boiling Hydrocarbon	U (W/m²K) C (£/(W/K))	270 3.10	402 3.10	NA	NA	453 3.10	NUS	NA	530 3.10	NUS
10000	Low Pressure Gas (<1 bar)	U (W/m²K) C (£/(W/K))	163 1.57	217 1.55	NA	NA	264 1.55	NUS	NUS	270 1.55	NUS
	Medium Pressure Gas (20 bar)	U (W/m²K) C (£/(W/K))	217 1.55	325 1.55	NA	NA	377 1.55	NUS	NUS	402 1.55	NUS
	High Pressure Gas (150 bar)	U (W/m²K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m²K) C (£/(W/K))	315 *1.55*	491 *1.55*	NA	NA	NUS	NUS	NUS	NUS	NUS
	Low Viscosity Hydrocarbon Liquid	U (W/m²K) C (£/(W/K))	NUS	NUS	NA	NA	NUS	NUS	NUS	NUS	NUS
	High Viscosity Hydrocarbon Liquid	U (W/m²K) C (£/(W/K))	NUS	NUS	NA	NUS	NUS	NUS	NUS	NUS	NUS
	Boiling Water	U (W/m²K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Boiling Hydrocarbon	U (W/m²K) C (£/(W/K))	270 *1.55*	402 1.55	NA	NA	453 1.55	NUS	NA	530 1.55	NUS

Table 3.6.8 - U and C Values for Plate-Fin Heat Exchangers (Courtesy of ESDU)

(Key: NA - Not Applicable; NUS - Not Common)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
30000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	163 0.677	217 0.607	NA	NA	264 0.574	NUS	NUS	270 0.579	NUS
	Medium Pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	217 0.607	325 0.551	NA	NA	377 0.537	NUS	NUS	402 0.532	NUS
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	315 0.560	491 0.513	NA	NA	NUS	NUS	NUS	NUS	NUS
	Low Viscosity Hydrocarbon Liquid	U (W/m^{2}K) C (£/(W/K))	NUS	NUS	NA	NA	NUS	NUS	NUS	NUS	NUS
	High Viscosity Hydrocarbon Liquid	U (W/m^{2}K) C (£/(W/K))	NUS	NUS	NA	NUS	NUS	NUS	NUS	NUS	NUS
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Boiling Hydrocarbon	U (W/m^{2}K) C (£/(W/K))	270 0.579	402 0.532	NA	NA	453 0.527	NUS	NA	530 0.518	NUS
100000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	163 0.336	217 0.301	NA	NA	264 0.280	NUS	NUS	270 0.273	NUS
	Medium Pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	217 0.301	325 0.245	NA	NA	377 0.231	NUS	NUS	402 0.227	NUS
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	315 0.250	491 0.210	NA	NA	NUS	NUS	NUS	NUS	NUS
	Low Viscosity Hydrocarbon Liquid	U (W/m^{2}K) C (£/(W/K))	NUS	NUS	NA	NA	NUS	NUS	NUS	NUS	NUS
	High Viscosity Hydrocarbon Liquid	U (W/m^{2}K) C (£/(W/K))	NUS	NUS	NA	NUS	NUS	NUS	NUS	NUS	NUS
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Boiling Hydrocarbon	U (W/m^{2}K) C (£/(W/K))	270 0.273	402 0.227	NA	NA	453 0.216	NUS	NA	530 0.205	NUS

Table 3.6.8 - U and C Values for Plate-Fin Heat Exchangers (Courtesy of ESDU)

(Key: NA - Not Applicable; NUS - Not Common)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1 000000	Low Pressure Gas (<1 bar)	U (W/m^2K) C (£/(W/K))	163 0.201	217 0.168	NA	NA	264 0.152	NUS	NUS	270 0.151	NUS
	Medium Pressure Gas (2O bar)	U (W/m^2K) C (£/(W/K))	217 0.168	325 0.139	NA	NA	377 0.128	NUS	NUS	402 0.126	NUS
	High Pressure Gas (15O bar)	U (W/m^2K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^2K) C (£/(W/K))	315 0.140	491 0.115	NA	NA	NUS	NUS	NUS	NUS	NUS
	Low Viscosity Hydrocarbon Liquid	U (W/m^2K) C (£/(W/K))	NUS	NUS	NA	NA	NUS	NUS	NUS	NUS	NUS
	High Viscosity Hydrocarbon Liquid	U (W/m^2K) C (£/(W/K))	NUS	NUS	NA	NUS	NUS	NUS	NUS	NUS	NUS
	Boiling Water	U (W/m^2K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Boiling Hydrocarbon	U (W/m^2K) C (£/(W/K))	270 0.151	402 0.126	NA	NA	453 0.119	NUS	NA	530 0.110	NUS

Note: The *C* values given in the above table are based on the assumption that the heat exchangers are made of brazed aluminium and are designed for pressures less than 25 bar and temperatures below 340 K. If the pressure is increased to 80 bar, the cost will increase approximately 1.25 times. If the heat exchangers are made from stainless steel, the cost will be about 3 times higher, and if made from titanium the cost will be about 5 times higher.

Table 3.6.9 – U and C Values for Welded Plate Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot-side Fluid								
			Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	78 8.1	106 8.0	NA	220 4.9	153 5.7	122 5.9	243 4.7	225 4.9	190 5.8
	Medium Pressure Gas (2O bar)	U (W/m^{2}K) C (£/(W/K))	103 8.1	256 7	NA	381 4.9	308 4.9	202 5.7	1021 4.0	708 3~7	600 4.36
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	158 5.6	349 4.9	NA	1328 3.7	380 4.1	228 4.9	1750 3.5	511 3~9	400 4.98
	Low Viscosity Organic Liquid	U (W/m^{2}K) C (£/(W/K))	143 5.1	297 5.6	NA	343 4.1	534 3.9	283 4.4	1085 3.8	701 3.7	600 4.36
	High Viscosity Liquid	U (W/m^{2}K) C (£/(W/K))	103 6.1	188 5.9	NA	215 4.8	271 4.6	167 5.1	363 3.9	311 4.1	220 4.91
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	170 5.20	350 4.90	NA	1400 3.60	500 3.90	250 4.32	1800 3.50	800 3.28	500 4.36
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	150 5.50	300 5.6	NA	1000 3.80	400 4.98	200 4.46	1200 3.70	600 4.36	400 4.98
5000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	77 4.02	114 3.4	NA	220 2.8	168 2.74	119 2.8	243 4.4	226 1.92	190 2.28
	Medium Pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	108 3.58	616 1.5	NA	1223 1.18	1110 1.22	357 1.98	1400 1.02	787 1.3	440 1.98
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	215 2.54	1187 1.22	NA	4252 0.74	1551 1.0	454 1.52	3880 0.7	1272 0.9	600 1.22
	Low Viscosity Organic Liquid	U (W/m^{2}K) C (£/(W/K))	140 2.94	975 1.22	NA	1650 0.82	1692 0.78	522 1.22	2676 0.78	1281 0.92	600 1.22
	High Viscosity Liquid	U (W/m^{2}K) C (£/(W/K))	131 2.8	357 0.9	NA	411 1.3	400 1.8	242 2.04	621 1.26	434 1.36	300 1.66
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	195 2.8	1000 1.28	NA	4500 0.78	2000 0.58	600 1.04	4000 0.75	1200 1.28	550 1.35
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	155 2.65	800 1.48	NA	2000 0.79	1500 0.80	500 1.25	2500 0.78	900 1.38	450 1.52

Table 3.6.9 – U and C Values for Welded Plate Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot-side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
30000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	83 2.33	133 1.8	NA	238 1.67	176 1.96	134 1.95	246 0.934	191 1.01	170 1.96
	Medium Pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	129 2.1	503 0.733	NA	1262 0.43	819 0.54	774 0.61	1384 0.494	850 0.634	440 0.52
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	210 1.53	1068 0.42	NA	9100 0.147	4268 0.26	2067 0.26	5465 0.18	1518 0.274	600 0.55
	Low Viscosity Organic Liquid	U (W/m^{2}K) C (£/(W/K))	141 1.82	1060 0.37	NA	3570 0.21	3763 0.194	1075 0.367	3652 0.214	1366 0.297	600 0.55
	High Viscosity Liquid	U (W/m^{2}K) C (£/(W/K))	131 1.9	298 0.87	NA	484 0.52	413 0.584	292 0.824	1626 0.287	403 0.54	300 0.87
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	220 1.51	1100 0.42	NA	9000 0.15	4500 0.25	2000 0.26	5500 0.18	1500 0.28	600 0.55
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	160 1.65	900 0.39	NA	5000 0.19	3500 0.20	1200 0.37	4000 0.26	1000 0.37	500 0.53
100000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	65 3.84	141 1.33	NA	230 1.42	167 1.74	141 2.0	246 1.06	190 0.92	170 1.75
	Medium Pressure Gas (2O bar)	U (W/m^{2}K) C (£/(W/K))	137 1.38	534 0.462	NA	1354 0.303	940 0.34	776 0.41	1342 0.238	834 0.307	440 0.51
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	223 1.37	1112 0.28	NA	9420 0.062	4858 0.108	2106 0.13	5071 0.085	1518 0.186	600 0.40
	Low Viscosity Organic Liquid	U (W/m^{2}K) C (£/(W/K))	157 1.71	722 0.36	NA	4140 0.118	3794 0.101	1277 0.19	3712 0.108	1367 0.161	600 0.40
	High Viscosity Liquid	U (W/m^{2}K) C (£/(W/K))	133 1.67	355 0.592	NA	530 0.42	415 0.538	302 0.515	1617 0.158	452 0.389	300 0.52
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	220 1.37	1100 0.28	NA	9000 0.063	4500 0.13	2000 0.15	5500 0.09	1500 0.17	600 0.40
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	160 1.71	900 0.32	NA	5000 0.12	3500 0.14	1200 0.19	4000 0.13	1000 0.30	500 0.43

Table 3.6.9 – U and C Values for Welded Plate Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot-side Fluid								
			Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1000000	Low Pressure Gas (<1 bar)	U (W/m^{2}K) C (£/(W/K))	*65* 3.84	141 1.33	NA	230 1.42	167 1.74	141 2.00	246 1.06	190 0.92	170 1.75
	Medium Pressure Gas (20 bar)	U (W/m^{2}K) C (£/(W/K))	137 1.38	504 0.41	NA	1334 0.22	989 0.242	787 0.282	1418 0.127	826 0.241	440 0.43
	High Pressure Gas (150 bar)	U (W/m^{2}K) C (£/(W/K))	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Treated Cooling Water	U (W/m^{2}K) C (£/(W/K))	223 1.37	1173 0.22	NA	9050 0.033	5061 0.045	2122 0.068	5460 0.038	1561 0.095	600 0.20
	Low Viscosity Organic Liquid	U (W/m^{2}K) C (£/(W/K))	157 1.71	927 0.23	NA	4880 0.04	4104 0.0505	1148 0.123	3828 0.048	1379 0.1	600 0.20
	High Viscosity Liquid	U (W/m^{2}K) C (£/(W/K))	133 1.67	323 0.49	NA	510 0.21	*553* 0.2	312 0.321	1714 0.081	434 0.241	300 0.33
	Boiling Water	U (W/m^{2}K) C (£/(W/K))	220 1.37	1100 0.12	NA	9000 0.033	4500 0.05	2000 0.07	5500 0.04	1500 0.10	600 0.20
	Boiling Organic Liquid	U (W/m^{2}K) C (£/(W/K))	160 1.71	900 0.14	NA	5000 0.05	3500 0.051	1200 0.13	4000 0.041	1000 0.12	500 0.22

Note: The C-values given in the above table are based on the assumption that the exchangers are constructed from stainless steel type 316 with a design pressure appropriate to the working pressure. The costs are valid up to 600°C. If the external vessel is constructed from carbon steel, the costs would be 20-40 per cent less depending on size and pressure.

Table 3.6.10 - U and C Values for Double Pipe Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1 bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
1000	Low Pressure Gas (< 1 bar)	U (W/m^2K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	4.8	3.8	2.9	3.8	3.8	4.7	2.8	3.8	3.9
	Medium Pressure Gas (20 bar)	U (W/m^2K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	3.4	2.5	2.9	2.5	5	2.6	2.5	2.5	2.5
	High Pressure Gas (150 bar)	U (W/m^2K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
	Treated Cooling Water	U (W/m^2K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	2.8	2.5	2.9	2.5	2.5	2.5	2.5	3.9	2.5
	Low Viscosity Hydrocarbon Liquid	U (W/m^2K)	100	375	425	600	500	130	820	525	290
		C (£/(W/K))	2.7	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5
	High Viscosity Hydrocarbon Liquid	U (W/m^2K)	70	140	175	160	155	85	175	155	125
		C (£/(W/K))	4.7	2.5	2.9	2.5	2.5	3.9	2.5	2.5	2.5
	Boiling Water	U (W/m^2K)	105	470	550	875	670	140	1435	725	340
		C (£/(W/K))	3.9	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5
	Boiling Organic Liquid	U (W/m^2K)	100	375	430	600	500	130	820	525	285
		C (£/(W/K))	4	2.5	2.9	2.5	2.5	2.5	2.5	2.5	2.5
5000	Low Pressure Gas (<1 bar)	U (W/m^2K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	2.16	1.26	1.1	1.23	1.22	1.84	1.23	1.22	3.5
	Medium pressure Gas (20 bar)	U (W/m^2K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	1.5	0.86	1	0.76	0.8	1.16	0.6	0.8	0.94
	High Pressure Gas(150 bar)	U (W/m^2K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.05	1.1	1.1	1	1.1	1.3	1	1.1	1.2
	Treated Cooling Water	U (W/m^2K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	1.4	0.75	1	0.5	0.72	1	0.4	0.72	0.9
	Low Viscosity Hydrocarbon Liquid	U (W/m^2K)	100	375	425	600	500	130	820	525	290
		C (£/(W/K))	1.45	0.8	1.05	0.8	0.9	1.1	0.5	0.9	1.2
	High Viscosity Hydrocarbon Liquid	U (W/m^2K)	70	140	175	160	155	85	175	155	125
		C (£/(W/K))	2.4	1.66	1.2	0.95	1	2.7	0.82	1.6	1.95
	Boiling Water	U (W/m^2K)	105	470	550	875	670	140	1435	725	340
		C (£/(W/K))	1.4	0.9	1	0.5	0.6	1.1	0.4	0.73	0.9
	Boiling Organic Liquid	U (W/m^2K)	100	375	430	600	500	130	820	525	285
		C (£/(W/K))	1.45	0.8	1.05	0.8	0.9	1.28	0.7	1	1.1

Table 3.6.10 - U and C Values for Double Pipe Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<1bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with Inert Gas
30000	Low Pressure Gas (<1 bar)	U (W/m^{2}K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	2.16	1.26	1.1	1.23	1.22	1.84	1.23	1.22	3.5
	Medium pressure Gas (20 bar)	U (W/m^{2}K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	1.5	0.43	0.35	0.27	0.33	1.16	0.23	3.07	0.42
	High Pressure Gas (150 bar)	U (W/m^{2}K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.05	0.4	0.36	0.27	0.33	1.5	0.24	0.3	0.35
	Treated Cooling Water	U (W/m^{2}K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	1.4	0.31	0.27	0.19	0.21	1	0.17	0.2	0.37
	Low Viscosity Hydrocarbon Liquid	U (W/m^{2}K)	100	375	425	600	500	130	820	*525*	290
		C (£/(W/K))	1.45	0.33	0.28	0.17	0.19	1.1	0.18	0.27	0.41
	High Viscosity Hydrocarbon Liquid	U (W/m^{2}K)	70	140	175	160	155	85	175	155	125
		C (£/(W/K))	2.4	1.8	***0.55***	0.62	0.65	2.7	1.66	0.68	1.95
	Boiling Water	U (W/m^{2}K)	105	470	*550*	875	670	140	1435	725	340
		C (£/(W/K))	1.4	0.26	0.25	0.17	0.21	1.1	0.17	0.2	0.36
	Boiling Organic Liquid	U (W/m^{2}K)	100	375	430	600	500	130	820	525	285
		C (£/(W/K))	1.45	0.33	0.31	0.22	0.24	1.28	0.2	0.23	0.46
100000	Low Pressure Gas (<1 bar)	U (W/m^{2}K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	2.16	1.26	1.1	1.23	1.22	1.84	1.23	1.22	3.5
	Medium Pressure Gas (20 bar)	U (W/m^{2}K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	1.5	0.43	0.35	0.27	0.33	1.16	0.18	3.07	0.42
	High Pressure Gas (150 bar)	U (W/m^{2}K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.05	0.4	0.36	0.27	0.33	1.5	0.2	0.3	0.35
	Treated Cooling Water	U (W/m^{2}K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	1.4	0.31	0.22	0.13	0.14	1	0.11	0.2	0.37
	Low Viscosity Hydrocarbon Liquid	U (W/m^{2}K)	100	375	425	600	500	130	820	*525*	290
		C (£/(W/K))	1.45	0.33	0.28	0.17	0.19	1.1	0.14	0.19	0.41
	High Viscosity Hydrocarbon Liquid	U (W/m^{2}K)	70	140	175	160	155	85	175	155	125
		C (£/(W/K))	2.4	1.8	0.55	0.62	0.65	2.7	1.66	0.68	1.95
	Boiling Water	U (W/m^{2}K)	105	470	550	875	670	140	1435	725	340
		C (£/(W/K))	1.4	0.26	0.25	0.14	0.16	1.1	0.11	0.14	0.36
	Boiling Organic Liquid	U (W/m^{2}K)	100	375	430	600	500	130	820	525	285
		C (£/(W/K))	1.45	0.33	0.31	0.17	0.23	1.28	0.12	0.23	0.46

Table 3.6.10 - U and C Values for Double Pipe Heat Exchangers (Courtesy of ESDU)

$\dot{Q}/\Delta T$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid: Low Pressure Gas (<I bar)	Medium Pressure Gas (20 bar)	High Pressure Gas (150 bar)	Process Water	Low Viscosity Hydrocarbon Liquid	High Viscosity Hydrocarbon Liquid	Condensing Steam	Condensing Hydrocarbon	Condensing Hydrocarbon with inert Gas
1000000	Low Pressure Gas (<1 bar)	U (W/m^2K)	55	95	125	105	100	65	110	100	85
		C (£/(W/K))	2.16	1.26	1.1	1.23	1.22	1.84	1.23	1.22	3.5
	Medium Pressure Gas (20 bar)	U (W/m^2K)	95	300	350	430	375	120	530	390	240
		C (£/(W/K))	1.5	0.43	0.35	0.27	0.33	1.16	0.18	3.07	0.42
	High Pressure Gas (150 bar)	U (W/m^2K)	120	350	400	500	400	150	600	420	350
		C (£/(W/K))	2.05	0.4	0.36	0.27	0.33	1.5	0.2	0.3	0.35
	Treated Cooling Water	U (W/m^2K)	105	484	500	940	715	145	1610	765	345
		C (£/(W/K))	1.4	0.31	0.22	0.13	0.14	1	0.11	0.2	0.37
	Low Viscosity Hydrocarbon Liquid	U (W/m^2K)	100	375	425	600	500	130	820	525	290
		C (£/(W/K))	1.45	0.33	0.28	0.17	0.19	1.1	0.14	0.19	0.41
	High Viscosity Hydrocarbon Liquid	U (W/m^2K)	70	140	175	160	155	85	175	155	125
		C (£/(W/K))	2.4	1.8	0.55	0.62	0.65	2.7	1.66	0.68	1.95
	Boiling Water	U (W/m^2K)	105	470	550	875	670	140	1435	725	340
		C (£/(W/K))	1.4	0.26	0.25	0.14	0.16	1.1	0.11	0.14	0.36
	Boiling Organic Liquid	U (W/m^2K)	100	375	430	600	500	130	820	525	285
		C (£/(W/K))	1.45	0.33	0.31	0.17	0.23	1.28	0.12	0.23	0.46

Note: Further information on costs for double pipe heat exchangers is given by G.P. Purohit ("Thermal and hydraulic design of hairpin and finned bundle exchangers", Chemical Engineering, Vol.90, No.10, pp.62-70, 1983).

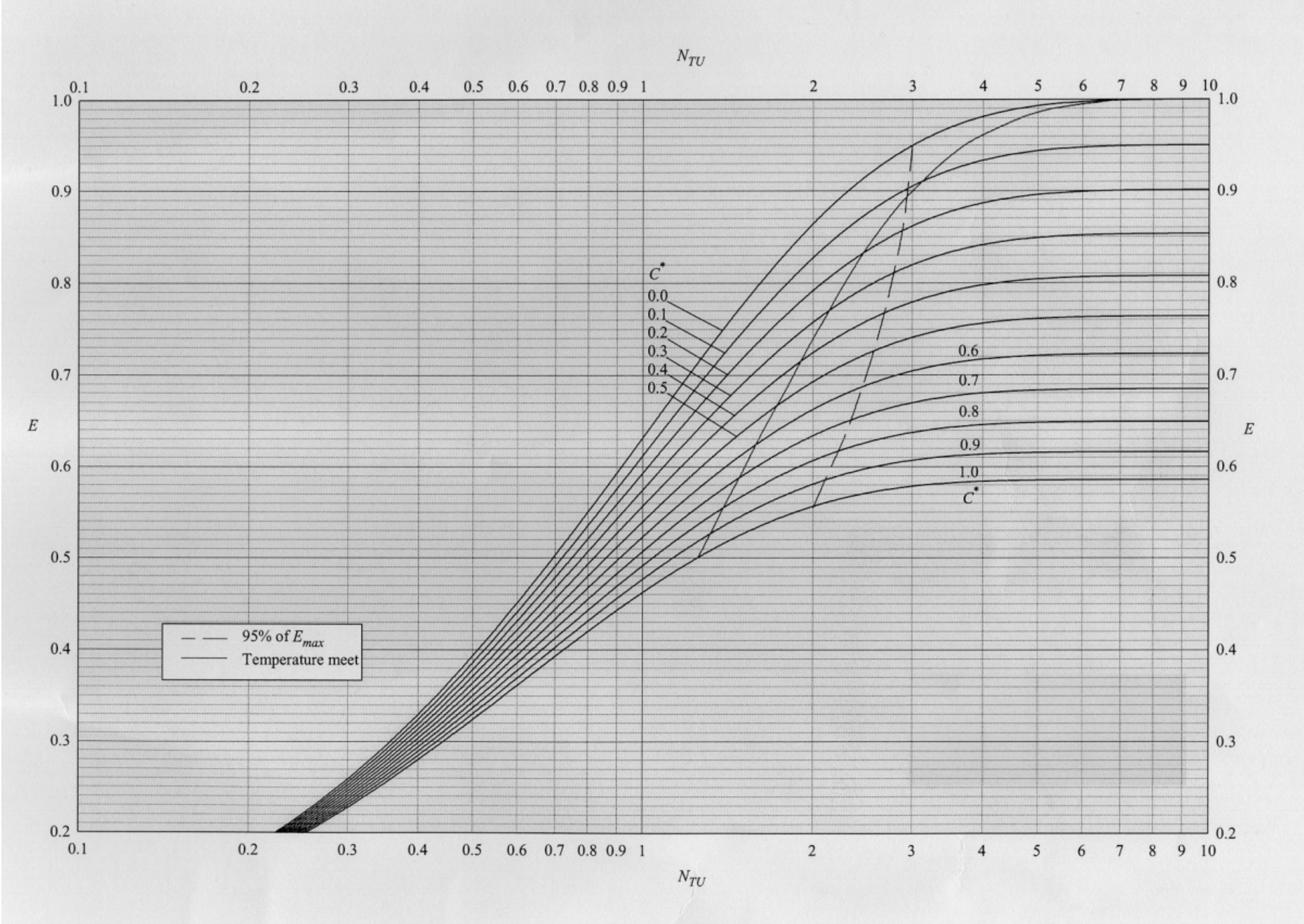


Figure 3.6.3 – E versus N_{TU} for a Shell and Tube Exchanger with an even number of tube side passes (Courtesy ESDU)

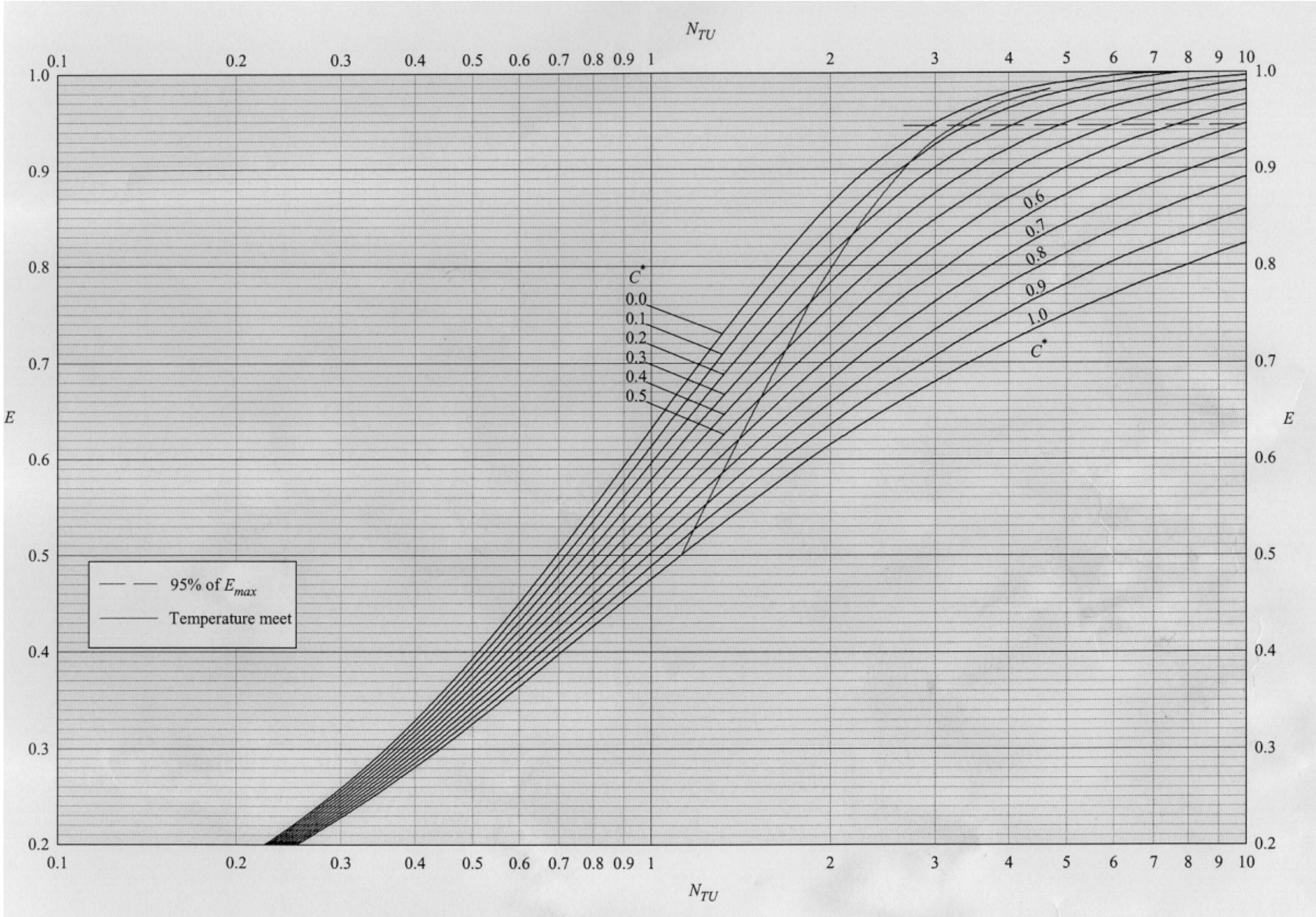


Figure 3.6.4 - E versus N_{TU} for an Unmixed Cross-Flow Exchanger
(Courtesy of ESDU)

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.7

PROCESS INTENSIFICATION

This module provides general information on process intensification and the use of compact heat exchanger designs as integrated reactor heat exchangers. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description of exchanger types, followed by information on construction, construction materials, operating limits and principal applications.

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3.7.1 Introduction
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3.7.3 HEX Reactor Designs
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PROCESS INTENSIFICATION

3.7.1 Introduction

Process intensification is a design philosophy for chemical plant that aims to achieve radical reductions in the size of the reaction plant and derive associated benefits.

An intensified process plant is one in which the same level of output is achieved from equipment that is significantly smaller than conventional designs. In theory any plant smaller than the conventional design represents an intensified plant, but in practice the convention is that process intensification relates to substantial reductions of at least 3 fold up to 1000 fold.

Intensifying chemical manufacturing plant can lead to a number of major benefits:

- Improved energy efficiency.
- Improved safety.
- Improved reaction control.
- Waste minimisation: reduced raw material consumption and less by-product formation.
- Reduced capital cost.
- Reduced environmental impact.

Process intensification is a broad topic that covers many technical areas including heat exchangers, reactors, separators, utility plant and overall plant design.

Within the area of reactor technology, existing conventional designs, such as jacketed stirred tank reactors, have limitations in terms of heat and mass transfer particularly for fast chemical reactions typical of the chemical industry. These limitations often affect the chemical reaction equilibrium in terms of product yield and by-product formation.

In batch processes there is scope for intensification by converting to continuous operation, by increasing heat transfer to and from the reactor and by improved mixing to increase mass transfer rates.

In continuously operated plant, there is scope for intensification by integrating reactors into a single item of equipment, by increasing heat transfer rates and by increasing reactor capacity per unit volume.

The Energy Efficiency Best Practice Programme and the European Commission have funded R&D projects to develop the concept and demonstrate the benefits of using compact heat exchanger designs as part of process intensification.

3.7.2 Integrated Reactor Heat Exchangers

The potential benefits of using compact integrated reactor heat exchangers (sometimes termed HEX reactors) are great, especially where exothermic reactions are involved. Existing technology allows compact heat exchanger flow channel designs to be engineered to optimise the heat and mass transfer criteria of a chemical reaction, which in turn allows maximum reaction yield, maximum heat transfer and minimum by-product formation.

The potential benefits of compact integrated exchanger reactors are:

- Reduced energy costs due to high thermal effectiveness; close approach temperatures, more efficient heat removal, less heat loss, elimination of mixing inefficiencies.
- Reduced capital cost through less material use, simpler installation, smaller footprint and weight.
- Improved safety because of smaller chemical inventory, better reaction control and rapid heat supply or removal.
- Increased throughputs by debottlenecking plants and increased cost-effectiveness of existing plants.
- Greater equipment flexibility, in the short term for rapid changes between small quantity, high value process runs, or in the medium term for rapid production response to changes in consumer demand.
- Higher purity products because equipment can be better optimised to reduce reaction by-products thereby minimising the need for downstream product processing, and unwanted by-product treatment and disposal.
- Waste minimisation due to minimised reactor volume for cleaning or sanitisation, less raw material consumption and less by-product production.

Compact integrated reactor heat exchanger development is an area of intense activity and further design innovations can be expected.

3.7.3 HEX Reactor Designs

The recent development of this technology means that there are few commercial HEX reactor designs available currently. Chart Marston Ltd, in conjunction with BHR Group, developed a novel compact heat exchanger reactor based on bonding stacks of plates previously photoetched to form a series of slots.

The exchanger design is patented under the “Marbond” trademark (see “Development of a Novel Integrated Chemical Reactor-heat Exchanger” by Phillips and Symonds available at www.bhrgroup.co.uk/mixing/piart1.htm).

The reactor matrix structure combines the heat transfer advantages of compact exchanger designs with a multi-pass capability enabling different reactant streams to be mixed and reacted under optimum mixing, thermal and residence time conditions.

Early testing of the "Marbond" design shows improved process selectivity; i.e. product yields increased and by-product formation reduced. These affects were attributed to:

- Superior mixing characteristics compared to a conventional plate-fin heat exchanger.
- Improved thermal characteristics approaching isothermal conditions.

The testing found that, in general, the benefits of using a combined reactor exchanger were greatest for more exothermic (or endothermic) reaction processes, when compared to the use of conventional equipment, such as jacketed stirred tanks or static mixer-reactors.

3.7.3.1 Construction

Metal plates are photochemically etched to form a series of slots. The plates are stacked with intervening solid separator plates and diffusion bonded (see module 2.2.3).

Adjacent flow streams are segregated by the intervening plates enabling separate flow paths to be formed across a series of plates, e.g. for reactants or heating/cooling fluids. Reactants are injected into flow streams by means of perforations in the separator plates.

Multi-point reactant injection results in heat release or uptake being evenly spread across the exchanger core ensuring very effective heat transfer with the heating or cooling fluid.

Plate materials include stainless steel and aluminium.

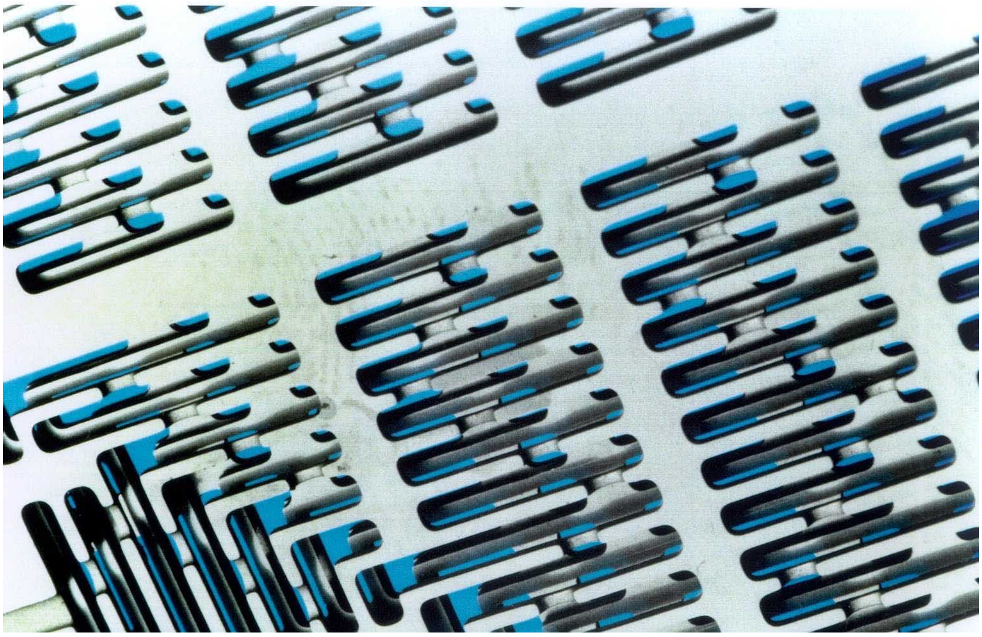

Figure 3.7.1 - Slotted Plates Forming Flow Paths
(Courtesy of Chart Marston Ltd)

3.7.3.2 Operating Limits

The operating range of this heat exchanger is a function of its construction materials.

As with other diffusion bonded exchanger designs, fluid streams in the “Marbond” reactors must be:

- Ideally free of particulates (although when some particles are inevitable, the heat transfer surface geometry can be adjusted to avoid blockage).
- Non-corrosive to the materials of construction.
- In the temperature range cryogenic to 900^{o}C (with the maximum operating temperature depending on plate materials, pressure, thermal cycling and other factors).
- Less than the maximum design pressure of 200 bar.

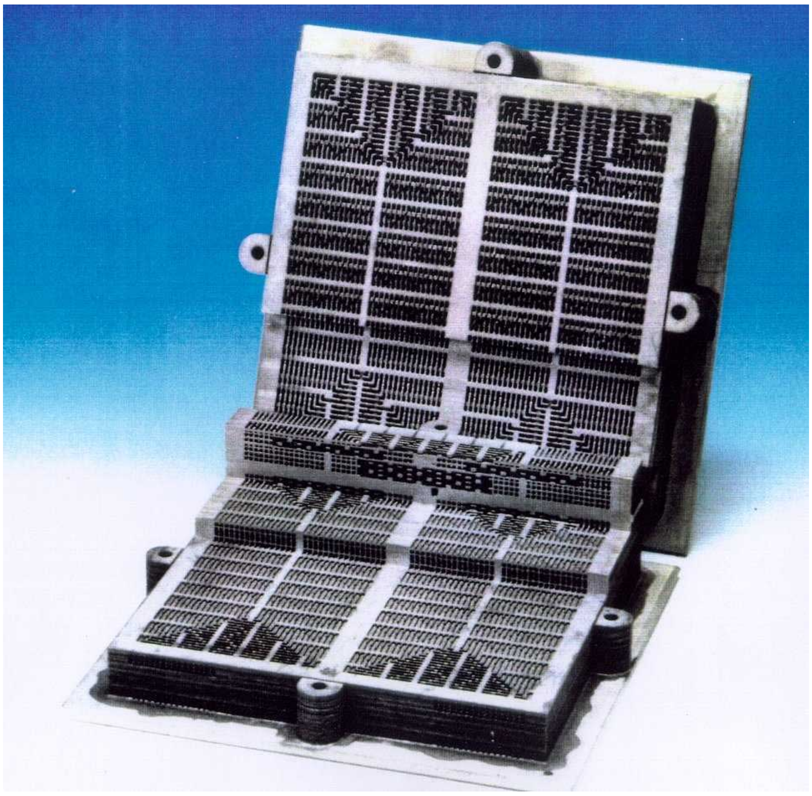

Figure 3.7.2 - Exploded View of a Marbond Unit
(Courtesy of Chart Marston Ltd)

3.7.3.3 Principal Applications

The manufacturer has identified the likely industrial applications for the “Marbond” technology as fast chemical reactions involving production or absorption of heat combined with the potential to form by-products.

Suitable reactions include nitrations, emulsifications, polymerisations, hydrogenations, sulphonations, alkylations, acylations, aminations and oxidations.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 3.8

SOFTWARE

This module presents general information on software available for heat exchanger selection. It is part of the series presenting information applicable to all technologies, such as general advantages and limitations of compact exchanger designs, common applications, fouling, energy efficiency, heat transfer enhancement, exchanger selection, specification and operation, process intensification and software programmes.

The Module 2 series contains a brief introductory description to the exchanger types, followed by information on the construction, construction materials, operating limits and principal applications.

Contents

3.8.1 Introduction
3.8.2 Initial Technology Selection Software
3.8.2.1 CHEX (Comparative Heat Exchanger Design Program)
3.8.2.2 (Heat Exchanger Advisor)

3.8.3 Primary Heat Exchanger Design Programs
3.8.4 Flowsheeting Software
3.8.4.1 HYSYS Program Suite
3.8.4.2 HYSIM

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3.8.1 Examples of Primary Heat Exchanger Software

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3.8.1 CHEX Screenshot – Composite Curves

SOFTWARE

3.8.1 Introduction

The practical selection of heat exchangers is a complex matter generally performed by a progressive series of actions.

- Initial feasibility/selection of generic heat exchanger types based on the duty required including pressures, temperatures, characteristics of hot and cold process streams, previous experience, physical footprint etc. This eliminates unsuitable technologies at the first stage and feeds forward potential technologies to a more detailed feasibility.
- Calculation of heat transfer areas including fouling characteristics for different exchanger configurations and different exchanger technologies. Includes process integration aspects.
- Comparative costing of heat exchanger options including construction materials.
- Final selection including all the previous aspects plus installation costs, operational costs, energy efficiency, safety implications, maintenance requirement and other associated selection criteria.

Various software programs are commercially available to help engineers interested in specifying compact heat exchangers or wishing to carry out a comparison of compact heat exchangers and conventional shell and tube heat exchangers.

Alternatively, equipment suppliers are able to size and cost heat exchanger options using their proprietary design software and given sufficient application information.

This section discusses software available free of charge or available on a commercial basis.

For convenience, current software is classified as:

- Initial heat exchanger technology selection software designed for junior engineers.
- Complex exchanger-specific primary software intended for detailed design evaluation/simulations incorporating many criteria.
- General flowsheeting and unit operations software including heat exchange.

Often an engineer at the conceptual stage is faced with the need to establish a flowsheet very quickly, and the flowsheet may need to be changed quickly. As a result there is no time to obtain quotes from suppliers, and the engineer may then resort to 'back-of-the-envelope' calculations, using typical coefficients to arrive at the heat transfer surface of a shell and tube heat exchanger design, from which the estimator can prepare a budget price.

Because many engineers do not have the experience (or suitable programs) to design compact heat exchangers, these exchangers are often not considered at the first stage. It then, invariably, becomes too late to include compact designs at a later stage. If the compact heat exchanger, with all its efficiency, space and weight advantages, is to be considered at all, it must be sized at the conceptual design stage.

The use of compact designs, where possible, will usually promote more efficient process heat exchange because of their ability to cope with long thermal duties (high external temperature crosses) more easily than the shell and tube type. More efficient heat exchange results in energy savings, as well as all the other benefits.

A number of software programs addressing heat exchanger design in isolation are presented below.

Warning
The listing of a software supplier does not constitute endorsement by the Government of either the product or the supplier's competence: nor does the omission of a supplier discriminate against that supplier's product or competence.

3.8.2 Initial Technology Selection Software

3.8.2.1 CHEX (Comparative Heat Exchanger Design Program)

CHEX is available free with Good Practice Guide 89, Guide to Compact Heat Exchangers. It enables engineers to assess the potential benefits of compact designs over conventional shell and tube exchangers at an early stage in their design concepts and may be used to facilitate budget preparation.

The software designs the following types of exchanger:

- TEMA shell and tube type NEN, BEU or BES as appropriate, in carbon steel.
- Plate and frame or brazed plate heat exchangers as appropriate in stainless steel or titanium, as selected by the user.
- Plate-fin heat exchanger in aluminium or stainless steel as selected by the user.
- Printed circuit heat exchangers in stainless steel.

CHEX is designed to illustrate the substantial savings in weight and space that can generally be achieved by using compact heat exchangers in place of shell and tube exchangers. It makes no estimate of cost, that being the specialised domain of vendors. The exchanger with smallest weight and/or space may not be the cheapest alternative.

CHEX is not intended to be used as a design program as it only allows comparison of alternatives. Where CHEX demonstrates significant benefits of compact heat exchangers over shell and tube exchangers it is likely that engineers will seek further advice from compact and shell and tube exchanger manufacturers, or use more sophisticated programs to confirm their designs. CHEX is designed to be used with the very minimum of information available to the conceptual design engineer.

As CHEX has been designed for use with two streams only it will not handle multi-streams. This simplification allows CHEX to be relatively uncomplicated, fast and easy to use. CHEX reports the design result for each heat exchanger type separately, including geometry, weight and surface. The overall sizes and weights are also shown pictorially, usually forcefully demonstrating the advantages of compact heat exchangers over conventional shell and tube types.

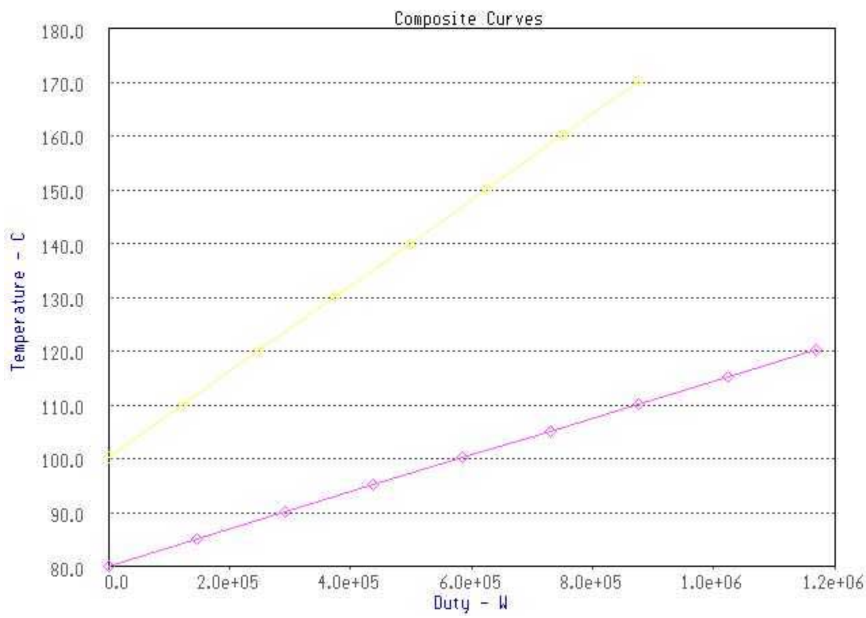

Figure 3.8.1 – CHEX Screen-shot: Example Composite Curves

3.8.2.2 Heat Exchanger Advisor

The Heat Exchanger Advisor (HEAd) software supplied by HTFS provides guidance on the best type of heat exchanger for a particular application. This commercial program takes account of a number of practical issues such as cost, plot area, fouling, pressure, temperature, material of construction, and fluid containment.

The software enables engineers to select the best heat exchanger type for a given process application, based on cost and technical suitability, and provides information on design, manufacture and operation.

The program covers:

- Heat exchanger types.
- Selection criteria – uses and operating limits.
- Design and manufacturing details.
- Cost implications of selection.

Associated with each heat exchanger type is a database that can be modified by the user to reflect company policy, experience and type preference. HEAd also has extensive on-line HELP facilities for all the heat exchangers listed.

3.8.3 Primary Heat Exchanger Design Programs

A number of companies produce primary programs dealing with heat exchanger design. Table 3.8.1 lists some commercially available software. For further details, contact the software supplier.

Program	Technology	Supplier
Devize	Shell and Tube	HTFS
MUSE	Plate-Fin	HTFS
APLE	Plate and Frame	HTFS
PHE	Plate and Frame	HTRI
ST	Shell and Tube	HTRI
CHED	Shell and Tube Matrix Plate-Fin	Sli – A Scientech Inc. Company

Table 3.8.1 – Examples of Primary Heat Exchanger Software

3.8.4 Flowsheeting Software

There are a large number of integrated process flowsheeting and process design software packages for the simulation and optimisation of static processes available on a commercial basis.

Heat exchange is one unit process of these simulators; the user usually selects the exchanger technology and may specify other criteria.

Some examples of this type of software are described below. Other software is available from AspenTech, NEL, ESDU and Linnhoff March.

A typical software suite available is illustrated in section 3.8.4.1.

3.8.4.1 HYSYS Program Suite

The HYSYS commercial software is supplied by Hyprotech.

The software can develop a single process model that can be used from conceptual design through on-line applications to improve designs, optimise production and enhance decision-making. It enables the integration of proprietary unit operations, reactions and property packages, and interaction with other applications.

<u>HYSYS.Concept</u>

This software designs and screens the most economical separation systems. It combines data regression, thermodynamic database access and the Mayflower distillation technology to enable the conceptual design of separation systems, including azeotropic and extractive distillation and non-ideal, heterogeneous or multiple liquid phase systems.

<u>HYSYS.Process</u>

This software function is process flowsheeting to maximize profitability of new designs and existing process operations. It is also used to model existing plants to ensure equipment is performing per specification, evaluate retrofits, and improve the process. Engineers engaged in process engineering design can use HYSYS.Process to screen alternative designs using efficient modelling and optimisation techniques.

<u>HYSYS.Plant</u>

This software is a plant modelling package to evaluate designs for profitability, operability, and safety and to improve plant operations. It allows engineers to incorporate steady state and dynamic modelling techniques to evaluate designs and rate existing plants. Simulations may be used to develop high fidelity operator training simulators, examine detailed unit and plant-wide performance, and simulate dangerous and non-profitable operating conditions to improve plant profitability and business performance.

3.8.4.2 HYSIM

Steady state flowsheet simulation software supplied by Hyprotech.

The HYSIM software was the first completely interactive steady state simulator and the first simulator created for the personal computer. HYSIM incorporates rigorous thermodynamic and physical property models, extensive component libraries, industry-proven oil characterisation, a wide range of unit operations and utilities (including tower and heat exchanger design and rating).

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 4.0

EXAMPLES

This module series presents worked examples of methods used to select between different types of heat exchanger.

Contents

4.1 Selection of a Welded Plate Heat Exchanger
4.2 Selection of a Gasketed Plate Heat Exchanger
4.3 Selection of a Plate-Fin Heat Exchanger
4.4 Selection of a Printed Circuit Heat Exchanger
4.5 Selection of a Shell and Tube Heat Exchanger

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 4.1

WORKED EXAMPLE 1
SELECTION OF A WELDED PLATE HEAT EXCHANGER

This module gives worked examples of the method used to select between different types of heat exchanger. Initially a coarse filter selects the exchangers that have the potential to satisfy the design criteria. A fine filter then assesses each option on the basis of cost.

This example is taken from ESDU Data Item 92013.

Output data from HEAd software is also provided to illustrate further aspects of selection.

Contents

4.1.1 Example
4.1.2 Method
4.1.3 Solution
4.1.4 Notation
4.1.5 HEAd – Heat Exchanger Advisor

List of Tables

4.1.1 Example Solution: Total Cost of Different Types of Heat Exchanger
4.1.2 HEAd Result Summary

List of Figures

4.1.1 HEAd Results

The following example includes an output from a commercially available software programme provided by HTFS. This information is presented to augment the ESDU methodology used and in no way constitutes an endorsement of the software, or the supplier, by the Government. Other software houses may be able to supply similar programs.

SELECTION OF A WELDED PLATE HEAT EXCHANGER

4.1.1 Example

<u>Heat Exchanger Duty</u>
Treated cooling water is used to cool an aqueous solution of an inorganic salt, which is at a pressure of 30 bar. The process stream enters the exchanger at 80°C and leaves at 60°C. The specific heat capacity of this stream is 3.8 kJ/kg.K and its flowrate is 100 kg/second. This stream can be treated as process water from the point of view of calculations of C values. The cooling water enters the heat exchanger at 20°C and leaves at 45°C. There is no significant fouling. Pressure drop assumed to be typical (1.0 bar).

Decide between the following exchanger options:

- Shell and Tube Heat Exchanger.
- Double Pipe Heat Exchanger.
- Gasketed Plate and Frame Heat Exchanger.
- Fully Welded Plate Heat Exchanger.
- Plate-Fin Heat Exchanger.

4.1.2 Method

Using Table 3.6.1, potential candidates for this duty are selected and then compared using the C-value method.

4.1.3 Solution

<u>Exclusions</u>
The pressure is too high for normal plate and frame heat exchangers (see Table 3.6.1).
Plate-fin heat exchangers are not normally considered for this type of duty (see Table 3.6.6).

The rate of cooling water is calculated from a heat balance:

$$\dot{M}_h Cp_h (T_{h,in} - T_{h,out}) = \dot{M}_c Cp_c (T_{c,out} - T_{c,in})$$

$$\dot{M}_c = \frac{\dot{M}_h Cp_h (T_{h,in} - T_{h,out})}{Cp_c (T_{c,out} - T_{c,in})} = \frac{100 \times 3.8 \times 10^3 \times (80-60)}{4.2 \times 10^3 \times (45-20)} = 72.38 \text{kg/s}$$

The heat load is calculated from

$$\dot{Q} = \dot{M}_h Cp_h (T_{h,in} - T_{h,out}) = 100 \times 3.8 \times 10^3 \times (80 - 60) = 7.6\text{MW}$$

The double pipe and welded plate heat exchangers may be considered as approximately counter-current heat exchangers. Therefore,

$$\Delta T_m = \Delta T_{lm} = \frac{\left[(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})\right]}{\log_e\left[(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})\right]}$$

$$\Delta T_m = \Delta T_{lm} = \frac{\left[(80-45)-(60-20)\right]}{\log_e\left[(80-45)/(60-20)\right]} = 37.44\text{K}$$

Thus

$$\frac{\dot{Q}}{\Delta T_m} = \frac{7.6 \times 10^6}{37.44} = 202991\text{W/K}$$

For the shell and tube exchanger (assumed to be in the conventional two-pass form) and for the printed circuit heat exchanger, if it is assumed to be in cross-flow mode (which is an unmixed cross-flow unit)[⊗], a correction factor is required to take account of the deviation from pure counter-current flow. First, the values of $\dot{M}Cp$ are calculated as follows.

$$\dot{M}_h Cp_h = 100 \times 3.8 \times 10^3 = 3.8 \times 10^5 \text{ W/K}$$

and $$\dot{M}_h Cp_c = 72.38 \times 4.2 \times 10^3 = 3.04 \times 10^5 \text{ W/K}$$

Thus

$$C^* = \frac{(\dot{M}Cp)_{smaller}}{(\dot{M}Cp)_{larger}} = \frac{3.04 \times 10^5}{3.8 \times 10^5} = 0.8$$

and $$E = \frac{(T_{in} - T_{out})_{larger}}{(T_{h,in} - T_{c,in})} = \frac{45-20}{80-20} = 0.4167$$

[⊗] Printed-circuit heat exchangers can also be operated in counter-current flow, but this would make little difference in this case.

From Figures 3.6.2 and 3.6.3, the values of N_{TU} corresponding to those values C^* and E are 0.72 and 0.70 for the two-pass shell and tube exchanger and unmixed cross-flow printed circuit heat exchangers, respectively. The values of $\dot{Q}/\Delta T_m$ follow from equation (3.6.7) for the shell and tube case as:

$$\frac{\dot{Q}}{\Delta T_m} = (\dot{M}Cp)_{smaller} N_{TU} = 3.04 \times 10^5 \times 0.72 = 218880 \text{W/K}$$

and for the printed circuit heat exchanger case as:

$$\frac{\dot{Q}}{\Delta T_m} = \left[\dot{M}Cp\right]_{smaller} N_{TU} = 3.04 \times 10^5 \times 0.70 = 212800 \text{W/K}$$

The values of C may be read from appropriate tables (Tables 3.6.3, 3.6.4, 3.6.5 and 3.6.7) and the calculated results are as follows:

Exchanger Type	$\left[\dot{Q}/\Delta T_m\right]_1$	**C_1**	$\left[\dot{Q}/\Delta T_m\right]_2$	**C_2**	**C**	**Total Cost**
	W/K	**£/(W/K)**	**(W/K)**	**£/(W/K)**	**£/(W/K)**	**£**
Shell and tube	100000	0.116	1000000	0.058	0.0916	20056
Double pipe	100000	0.130	1000000	0.130	0.1300	26388
Printed circuit	100000	0.330	300000	0.220	0.2490	53142
Welded plate	100000	0.062	1000000	0.033	0.0511	10367

Table 4.1.1 – Example Solution: Total Cost of Different Types of Heat Exchanger

Here the welded plate heat exchanger is significantly cheaper than any of the alternatives and is the obvious choice. However, such exchangers can only be used for low fouling duties.

For the example duty, the welded plate exchanger is selected for further evaluation and detailed design.

4.1.4 Notation

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q} / \Delta T$	£/(W/K)
C*	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
F_T	logarithmic temperature difference correction factor	-
h	specific enthalpy	J/kg
$\dot{M}$	mass flow-rate	kg/s
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R_K	$(\dot{M}Cp)_h / (\dot{M}Cp)_c$	-
T	stream temperature	K
U	overall heat transfer coefficient	W/m^2K
ΔT	temperature difference	K

Subscripts

c, h	refer to cold stream and hot stream, respectively.
fg	refers to phase change between liquid and gas.
in, out	refer to values of parameter at inlet to and outlet from heat exchanger, respectively.
larger, smaller	refer to the larger and smaller value of the parameter in streams, respectively.

4.1.5 HEAd – Heat Exchanger Advisor

The Heat Exchanger Advisor HEAd software (supplied by HTFS) makes initial heat exchanger selections to use for a specific process.

The function of this selection is:

- To exclude unsuitable heat exchangers.
- Rank the remainder on the grounds of cost.

Costs are based on ESDU Data Item 92013, "Selection and Costing of Heat Exchangers" using the same methods as outlined in Section 3.6. The data published in these tables (collated in 1992) are used to calculate a cost for all heat exchanger types except double pipes. The double pipe exchanger data used for these have been updated to allow for changes to the technology that decrease the cost in almost all cases.

The HTFS Heat Exchanger Advisor assesses whether any changes need by applied to the basic heat exchanger designs assumed by ESDU in order to handle the specified process. The ESDU costs are adjusted accordingly.

The HEAd software gives the following results for the selection of heat exchangers in this case:

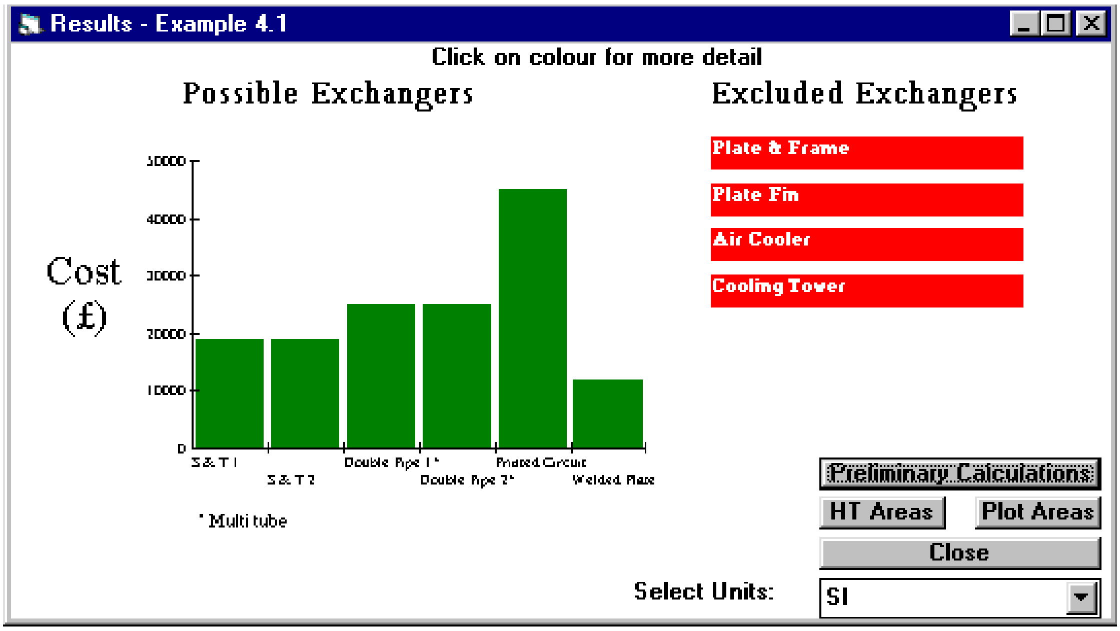

Figure 4.1.1 – HEAd Results
(Courtesy of HTFS)

For this example, four exchanger types were rejected. The reasons for rejection of each type were:

- Plate and Frame: Design pressure too high (limit = 3 MPa).
- Plate-Fin: Specified fluid combination not applicable to this heat exchanger.
- Air Cooler: Gaseous ambient air stream is required for this heat exchanger. Air-side design temperature is too high (limit = 313 K).
- Cooling Tower: Gaseous ambient air stream is required for this heat exchanger. Max design temperature is too high (limit = 333 K).

The remaining options were viable, but differentiated on the basis of cost.

Heat Exchanger Type	**Material Selection Details**	**Overall Heat Transfer Coefficient (W/m^2K)**	**Heat Transfer Area (m^2)**	**Cost**	**Variation**
Shell and Tube	Shell side and Tube side are Carbon Steel	938	230.8	£19905	U Tubes due to large temperature differential so lower cost
Double Pipe	Shell side and Tube side are Carbon Steel	940	215.9	£25187	More recent data used. Costs have decreased.
Printed Circuit	Stainless Steel	3230	62.8	£45366	HEAd assumed counter-current flow, rather than the cross-flow in the example.
Welded Plate	Stainless Steel	9305	21.8	£10366	None

Table 4.1.2 – HEAd Result Summary

In this example the welded plate design is clearly selected for further evaluation and detailed design.

This selection table can be compared to Table 4.1.2 that also selects the welded plate design.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 4.2

WORKED EXAMPLE 2
SELECTION OF A GASKETED PLATE HEAT EXCHANGER

This module gives worked examples of the method used to select between different types of heat exchanger. Initially a coarse filter selects the exchangers that have the potential to satisfy the design criteria. A fine filter then assesses each option on the basis of cost.

This example is taken from ESDU Data Item 92013.

Contents

4.2.1 Example
4.2.2 Method
4.2.3 Solution
4.2.4 Notation

List of Tables

4.2.1 Example Solution: Total Cost of Different Types of Heat Exchanger

SELECTION OF A GASKETED PLATE HEAT EXCHANGER

4.2.1 Example

A heat exchanger is required to cool process water flowing at 40 kg/s from a temperature of 120°C to a temperature of 40°C using cooling water at the same flowrate with an inlet temperature of 20°C and an outlet temperature of 100°C. The specific heat capacity of the water is 4.2 kJ/kg.K and the pressure of the two streams is around 5 bar. Evaluate the various options for this case and on the basis of the costs estimated from Tables 3.6.3 to 3.6.8, select the most economic case.

4.2.2 Method

The options are examined for feasibility and then costed approximately using the C-value method.

4.2.3 Solution

At 5 bar pressure the following heat exchangers are possible options:

- Gasketed plate.
- Double pipe.
- Shell and tube.

The process water fouling precludes the use of the plate-fin, welded plate and printed circuit heat exchangers.

The heat load is calculated as follows:

$$\dot{Q} = \dot{M}_h Cp_h (T_{h,in} - T_{h,out}) = 40 \times 4.2 \times 10^3 \times [120 - 40] = 13.44\text{MW}$$

For this case

$$(\dot{M}Cp)_{hot} = 40 \times 4.2 = 168\text{kW/K}$$

$$(\dot{M}Cp)_{cold} = 40 \times 4.2 = 168\text{kW/K}$$

Thus $C^* = 1$. The value of E is given by the equation:

$$E = \frac{(T_{in} - T_{out})_{larger}}{(T_{h,in} - T_{c,in})} = \frac{120-40}{120-20} = 0.8$$

As will be seen from Figure 3.6.2, there are no solutions for N_{TU} for these values of C^* and E, the particular case, therefore, being impossible with a shell and tube heat exchanger with two tube side passes. A counter-current flow shell and tube exchanger is therefore required and there is likely to be some economic penalty with this relative to a conventional multi-pass design. However, the C-values for a conventional design may be used with caution. The double pipe heat exchanger and plate and frame heat exchangers are usually operated in counter-current mode.

In this particular case, because of the balance between the two streams, the temperature difference is constant at 20K so that $\Delta T_m = 20\text{K}$. Thus:

$$\frac{\dot{Q}}{\Delta T_m} = \frac{13.44\times10^6}{20} = 6.72\times10^5\ \text{W/K}$$

The costs for the three alternative heat exchangers are now examined by logarithmically interpolating from tables 3.6.3, 3.6.4 and 3.6.8.

Suppose there is a value C_1 at $\left[\dot{Q}/\Delta T_m\right]_1$ and a value C_2 at $\left[\dot{Q}/\Delta T_m\right]_2$; the C value for the calculated $\dot{Q}/\Delta T_m$ is given by logarithmic interpolation and is as follows:

$$C = \exp\left\{\log_e C_1 + \frac{\log_e(C_1/C_2).\log_e\left[(\dot{Q}/\Delta T_m)/(\dot{Q}/\Delta T_m)_1\right]}{\log_e\left[(\dot{Q}/\Delta T_m)_1/(\dot{Q}/\Delta T_m)_2\right]}\right\}$$

Exchanger Type	$\left[\dot{Q}/\Delta T_m\right]_1$	**C_1**	$\left[\dot{Q}/\Delta T_m\right]_2$	**C_2**	**C**	**Total Cost**
	W/K	**£/(W/K)**	**(W/K)**	**£/(W/K)**	**£/(W/K)**	**£**
Shell and tube	100000	0.116	1000000	0.058	0.0654	43930
Double pipe	100000	0.130	1000000	0.130	0.1300	87360
Gasketed plate	100000	0.025	1000000	0.015	0.0164	11009

Table 4.2.1 – Example Solution: Total Cost of the Different Types of Heat Exchanger

Here, the economics of scale of the larger shell and tube exchangers prevail over the modular design of the double pipe exchanger. However, the gasketed plate exchanger would only cost about one quarter of the shell and tube exchanger and is the natural choice wherever feasible.

4.2.4 Notation

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q}/\Delta T$	£/(W/K)
C^*	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
F_T	logarithmic temperature difference correction factor	-
h	specific enthalpy	J/kg
$\dot{M}$	mass flow-rate	kg/s
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R_K	$(\dot{M}Cp)_h/(\dot{M}Cp)_c$	-
T	stream temperature	K
U	overall heat transfer coefficient	W/m^2K
ΔT	temperature difference	K

Subscripts

c, h	refer to cold stream and hot stream, respectively.
fg	refers to phase change between liquid and gas.
in, out	refer to values of parameter at inlet to and outlet from heat exchanger, respectively.
larger, smaller	refer to the larger and smaller value of the parameter in streams, respectively.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 4.3

WORKED EXAMPLE 3
SELECTION OF A PLATE-FIN EXCHANGER

This module gives worked examples of the method used to select between different types of heat exchanger. Initially a coarse filter selects the exchangers that have the potential to satisfy the design criteria. A fine filter then assesses each option on the basis of cost.

This example is taken from ESDU Data Item 92013.

Contents

4.3.1 Example
4.3.2 Method
4.3.3 Solution
4.3.4 Notation

List of Tables

4.3.1 Example Solution: Total cost of different types of heat exchanger
4.3.2 Example Solution: Volume of different types of heat exchanger

SELECTION OF A PLATE-FIN HEAT EXCHANGER

4.3.1 Example

A heat exchanger is required for a skid-mounted process plant. The exchanger condenses an organic vapour at –60°C on one side and boils an organic liquid at –100°C on the other side. The condensing vapour has a flow rate of 10 kg/s and is totally condensed (but not sub-cooled) in the unit. The system pressure is 70 bar and the latent heat of condensing vapour is 400 kJ/kg. The volume of the unit must not exceed $0.5 m^3$. Using Table 3.6.1, select alternative options for the heat exchanger type and evaluate the various options on the grounds of cost and volume.

4.3.2 Method

The options listed in Table 3.6.1 are evaluated. The C-value method is then used to evaluate the cost of these options and approximate volumes are calculated. The heat exchanger of least cost that meets the volume specification is then selected.

4.3.3 Solution

For this case the possible options are the shell and tube, double pipe, plate-fin and printed circuit heat exchanger. The heat load is given by:

$$\dot{Q} = 10 \times 400 \times 10^3 = 4\text{MW}$$

and the temperature difference is constant at 40K. Thus:

$$\frac{\dot{Q}}{\Delta T_m} = 100000$$

C-values for this value of $\dot{Q}/\Delta T_m$ are given directly from the tables without the need for logarithmic interpolation.

The costs for the shell and tube and double pipe heat exchangers, given in tables 3.6.3 and 3.6.8 respectively, are based on carbon steel construction. Carbon steel is not suitable for the low temperature and stainless steel would probably be used. This would increase the cost by a factor of around 2.

The costs for the various options are estimated as follows:

Exchanger type	C	Total Cost
	£/(W/K)	£
Shell and Tube	0.316	31600
Double Pipe	0.460	46000
Printed Circuit	0.580	58000
Plate-Fin	0.205	20500

Table 4.3.1 – Example Solution: Total Cost of the Different Types of Heat Exchanger

Clearly the plate-fin exchanger is the cheapest. Furthermore, there is also a specification of the maximum volume. The heat exchanger volume may be calculated approximately by assuming an area of $50m^2/m^3$ for shell and tube and double pipe heat exchangers and $500m^2/m^3$ for the printed circuit and plate-fin units. The area A is given by $(\dot{Q}/\Delta T_m)/U$ and the volumes are calculated as follows, using the values of U from the tables.

Exchanger Type	U	A	Volume
	W/m^2K	m^2	m^3
Shell and Tube	524	191	3.82
Double Pipe	525	190	3.80
Printed Circuit	982	101	0.202
Plate Fin	530	188	0.376

Table 4.3.2 – Example Solution: Volume of Different Types of Heat Exchanger

Thus, both the printed circuit and plate-fin designs fit the volume specification (less than $0.5\ m^3$). The plate-fin unit is considerably cheaper for this duty and would be the one chosen.

4.3.4 Notation

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q} / \Delta T$	£/(W/K)
C*	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
F_T	logarithmic temperature difference correction factor	-
h	specific enthalpy	J/kg
$\dot{M}$	mass flow-rate	kg/s
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R_K	$(\dot{M}Cp)_h/(\dot{M}Cp)_c$	-
T	stream temperature	K
U	overall heat transfer coefficient	W/m^2K
ΔT	temperature difference	K

Subscripts

c, h	refer to cold stream and hot stream, respectively.
fg	refers to phase change between liquid and gas.
in, out	refer to values of parameter at inlet to and outlet from heat exchanger, respectively.
larger, smaller	refer to the larger and smaller value of the parameter in streams, respectively.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 4.4

WORKED EXAMPLE 4
SELECTION OF A PRINTED CIRCUIT HEAT EXCHANGER

This module gives worked examples of the method used to select between different types of heat exchanger. Initially a coarse filter selects the exchangers that have the potential to satisfy the design criteria. A fine filter then assesses each option on the basis of cost.

This example is taken from ESDU Data Item 92013.

Contents

4.4.1 Example
4.4.2 Method
4.4.3 Solution
4.4.4 Notation

List of Tables

4.4.1 Example Solution: Total Cost of Different Types of Heat Exchanger
4.4.2 Example Solution: Overall Cost of Different Types of Heat Exchanger

SELECTION OF A PRINTED CIRCUIT HEAT EXCHANGER

4.4.1 Example

An export gas cooler is required for an offshore platform, cooling the gas from 150^{o}C to 50^{o}C at 150 bar (15 MPa). The gas has a flowrate of 20 kg/s and has a specific heat capacity of 2.6 kJ/kg.K. The coolant is treated as cooling water that enters the cooler at 15^{o}C, leaves at 60^{o}C and has a specific heat capacity of 4.2 kJ/kg.K. Fouling is expected to be minimal, but size is important since the volume occupied on the platform is estimated to cost £120000/m^3. Establish the feasible options and compare them on the basis of cost.

4.4.2 Method

Possible options are established on the basis of table 3.6.1 and are then compared using the C-value technique with the aid of Tables 3.6.3 to 3.6.8.

4.4.3 Solution

The high pressure rules out the use of the aluminium plate-fin, plate and frame and welded plate exchangers. The choice lies, therefore, between shell and tube, double pipe and printed circuit exchangers. The heat load, $\dot{Q}$, is given by:

$$\dot{Q} = \dot{M}_h Cp_h (T_{h,in} - T_{h,out}) = 20 \times 2.6 \times 10^3 \times (150 - 50) = 5.2\text{MW}$$

The flow rate of the coolant is established from the heat balance. Therefore:

$$\dot{M}_h Cp_h (T_{h,in} - T_{h,out}) = \dot{M}_c Cp_c (T_{c,out} - T_{c,in})$$

$$\dot{M}_c = \frac{\dot{M}_h Cp_h (T_{h,in} - T_{h,out})}{Cp_c (T_{c,out} - T_{c,in})} = \frac{20 \times 2.6 \times 10^3 \times (150 - 50)}{4.2 \times 10^3 \times (60 - 15)} = 27.51\text{kg/s}$$

If the shell and tube heat exchanger is multi-pass (the most widely used), the value of $\dot{Q}/\Delta T_m$ is calculated using the Effectiveness method.

$$E = \frac{(T_{in} - T_{out})_{larger}}{T_{h,in} - T_{c,in}} = \frac{150 - 50}{150 - 15} = 0.7407$$

The values of $\dot{M}Cp$ are calculated for the gas and water streams as follows:

$$(\dot{M}Cp)_{gas} = 20 \times 2.6 \times 10^3 = 52 kW/K$$

$$(\dot{M}Cp)_{water} = 27.51 \times 4.2 \times 10^3 = 115.5 kW/K$$

Thus:

$$C* = \frac{(\dot{M}Cp)_{smaller}}{(\dot{M}Cp)_{larger}} = \frac{52}{115.5} = 0.4502$$

From Figure 3.6.3, the value of N_{TU} corresponding to these values of E and $C*$ is 2.15.

$$\frac{\dot{Q}}{\Delta T_m} = [\dot{M}Cp]_{smaller} N_{TU} = 52000 \times 2.15 = 111000 W/K$$

For the double pipe exchanger, counter-current flow may be assumed. Thus:

$$\Delta T_m = \Delta T_{lm} = \frac{[(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})]}{\log_e[(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})]}$$

$$\Delta T_m = \Delta T_{lm} = \frac{[(150-60)-(50-15)]}{\log_e[(150-60)/(50-15)]} = 58.23 K$$

$$\frac{\dot{Q}}{\Delta T_m} = \frac{5.2 \times 10^6}{58.23} = 89301 W/K$$

If it is assumed that the printed circuit heat exchanger is operating as an unmixed crossflow device[⊗], the value of N_{TU} can be read from Figure 3.6.3 using the values of E and $C*$ calculated above. This yields a value of N_{TU} of 1.95. Thus:

$$\frac{\dot{Q}}{\Delta T_m} = [\dot{M}Cp]_{smaller} N_{TU} = 52000 \times 1.95 = 101400 W/K$$

[⊗] Printed-circuit heat exchangers can also be operated in counter-current flow

Using the logarithmic interpolation to obtain results for values of $\dot{Q}/\Delta T_m$ in between the published values, the following results are obtained:

Exchanger Type	$\left[\dot{Q}/\Delta T_m\right]_1$	C_1	$\left[\dot{Q}/\Delta T_m\right]_2$	C_2	C	Total Cost
	W/K	£/(W/K)	(W/K)	£/(W/K)	£/(W/K)	£
Shell and tube	100000	0.24	1000000	0.19	0.237	26530
Double pipe	100000	0.22	1000000	0.22	0.220	19646
Printed circuit	100000	0.46	300000	0.35	0.458	46482

Table 4.4.1 - Example Solution: Total Cost of Different Types of Heat Exchanger

Though the costs of the double pipe and shell and tube heat exchangers are less than that of the printed circuit heat exchanger, the cost of space on the offshore installations has also to be considered. Using the U values for this duty as given in tables 3.6.3, 3.6.5 and 3.6.8, the surface area required is given as:

$$A = \frac{\dot{Q}/\Delta T_m}{U}$$

and using the guidelines for surface area per unit volume of 50 m^2/m^3 for shell and tube and double pipe designs and 500 m^2/m^3 for the printed circuit exchanger, the following values are obtained for volume and total cost (including the cost of the space):

Exchanger Type	U	A	Volume	Total Cost
	W/m^2K	m^2	m^3	£
Shell and Tube	600	186.6	3.73	71290
Double Pipe	500	178.6	3.57	62486
Printed Circuit	2496	40.6	0.0803	47445

Table 4.4.2 - Example Solution: Overall Cost of Different Types of Heat Exchanger

Thus the overall cost for the printed circuit heat exchanger is considerably lower than that for the shell and tube and double pipe designs. Note that the volume is over 30 times smaller for the printed circuit design; the very small size allows it to be used in situations where it would be impossible to fit in a more conventional design.

4.4.4 Notation

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q}/\Delta T$	£/(W/K)
$C*$	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
F_T	logarithmic temperature difference correction factor	-
h	specific enthalpy	J/kg
$\dot{M}$	mass flow-rate	kg/s
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R_K	$(\dot{M}Cp)_h/(\dot{M}Cp)_c$	-
T	stream temperature	K
U	overall heat transfer coefficient	W/m^2K
ΔT	temperature difference	K

Subscripts

c, h	refer to cold stream and hot stream, respectively.
fg	refers to phase change between liquid and gas.
in, out	refer to values of parameter at inlet to and outlet from heat exchanger, respectively.
larger, smaller	refer to the larger and smaller value of the parameter in streams, respectively.

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MODULE 4.5

WORKED EXAMPLE 5
SELECTION OF A SHELL AND TUBE HEAT EXCHANGER

This module gives worked examples of the method used to select between different types of heat exchanger. Initially a coarse filter selects the exchangers that have the potential to satisfy the design criteria. A fine filter then assesses each option on the basis of cost.

This example is taken from ESDU Data Item 92013.

Contents

4.5.1 Example
4.5.2 Method
4.5.3 Solution
4.5.4 Notation

List of Tables

4.5.1 Example Solution: Total Cost of Different Types of Heat Exchanger

SELECTION OF A SHELL AND TUBE HEAT EXCHANGER

4.5.1 Example

A light hydrocarbon vapour is to be condensed under saturation conditions at a temperature of 120°C. It enters the condenser as a saturated vapour and leaves as saturated condensate. It is flowing at a rate of 300 kg/s and has a latent heat of condensation of 200 kJ/kg. The coolant is treated cooling water entering the system at 20°C and leaving at 50°C. Occasional mechanical cleaning of the condensing vapour side is necessary because of the deposition of a solid which is not chemically clearable. Assess the alternative options for this duty and carry out an approximate costing using the C-value method in order to select the most economic option.

4.5.2 Method

Possible options are established on the basis of Table 3.6.1 and are then compared using the C-value technique with the aid of Tables 3.6.3 to 3.6.8.

4.5.3 Solution

The gasketed plate exchanger is not usually suitable for the condensing hydrocarbon duty. The welded plate, plate-fin and printed circuit design are ruled out on the grounds of the need for physical cleaning. Thus, the choice is between shell and tube and double pipe designs. The heat load is given by:

$$\dot{Q} = \dot{M}_h h_{fg,h} = 300 \times 200 \times 10^3 = 60\text{MW}$$

With condensation at constant temperature, $\Delta T_m = \Delta T_{lm}$ irrespective of pass configuration. Thus:

$$\Delta T_m = \Delta T_{lm} = \frac{\left[(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})\right]}{\log_e\left[(T_{h,in} - T_{c,out})/(T_{h,out} - T_{c,in})\right]}$$

$$\Delta T_m = \Delta T_{lm} = \frac{\left[(120 - 50) - (120 - 20)\right]}{\log_e\left[(120 - 50)/(120 - 20)\right]} = 84.1\text{K}$$

$$\frac{\dot{Q}}{\Delta T_m} = \frac{60 \times 10^6}{84.1} = 7.134 \times 10^5 \text{ W/K}$$

To estimate the costs of these alternative designs, the C-value tables, Tables 3.6.3 to 3.6.8, are used. Suppose there is a value C_1 at $(\dot{Q}/\Delta T_m)_1$ and a value C_2 at $(\dot{Q}/\Delta T_m)_2$; the C-value for the calculated $\dot{Q}/\Delta T_m$ is given by logarithmic interpolation and is as follows:

$$C = \exp\left\{\log_e C_1 + \frac{\log_e (C_1/C_2)\log_e\left[(\dot{Q}/\Delta T_m)/(\dot{Q}/\Delta T_m)_1\right]}{\log_e\left[(\dot{Q}/\Delta T_m)_1/(\dot{Q}/\Delta T_m)_2\right]}\right\}$$

For the shell and tube heat exchanger from Table 3.6.3 with "Treated Cooling Water" and "Condensing Hydrocarbon" as the cold and hot fluids respectively.

$C_1 = 0.129$ at $(\dot{Q}/\Delta T_m)_1 = 100000$
$C_2 = 0.069$ at $(\dot{Q}/\Delta T_m)_2 = 1000000$

Thus for $(\dot{Q}/\Delta T_m) = 713400$, $C = 0.0756$

Exchanger Type	$\left[\dot{Q}/\Delta T_m\right]_1$	**C_1**	$\left[\dot{Q}/\Delta T_m\right]_2$	**C_2**	**C**	**Total Cost**
	W/K	**£/(W/K)**	**(W/K)**	**£/(W/K)**	**£/(W/K)**	**£**
Shell and tube	100000	0.129	1000000	0.069	0.0756	53955
Double pipe	100000	0.200	1000000	0.200	0.2000	142700

Table 4.5.1 - Example Solution: Total Cost of Different Types of Heat Exchanger

Here, the economy of scale of the shell and tube heat exchanger prevails over the modular nature of the double pipe heat exchanger and the former is the more economic choice.

4.5.4 Notation

A	heat transfer surface area of heat exchanger	m^2
Cp	specific heat capacity	J/kg.K
C	cost per unit $\dot{Q} / \Delta T$	£/(W/K)
C*	flow heat capacity ratio	-
E	heat exchanger effectiveness	-
F_T	logarithmic temperature difference correction factor	-
h	specific enthalpy	J/kg
$\dot{M}$	mass flow-rate	kg/s
N_{TU}	number of transfer units	-
P	flow heat capacity ratio	-
$\dot{Q}$	heat load of heat exchanger	W
$\dot{Q}_{max}$	maximum possible heat load	W
R_K	$(\dot{M}Cp)_h / (\dot{M}Cp)_c$	-
T	stream temperature	K
U	overall heat transfer coefficient	W/m^2K
ΔT	temperature difference	K

Subscripts

c, h	refer to cold stream and hot stream, respectively.
fg	refers to phase change between liquid and gas.
in, out	refer to values of parameter at inlet to and outlet from heat exchanger, respectively.
larger, smaller	refer to the larger and smaller value of the parameter in streams, respectively.

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 5.0

OTHER INFORMATION

This module series presents further information including a bibliography, contact details for compact heat exchanger technology suppliers and the Energy Efficiency Best Practice Programme.

Contents

5.1	Bibliography
5.2	Further Information
5.3	Technology Suppliers
5.4	Energy Efficiency Best Practice Programme

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 5.1

BIBLIOGRAPHY

This module provides a list of information sources used in the handbook.

Contents

5.1.1 Introduction
5.1.2 Energy Efficiency Best Practice Programme Publications
5.1.3 External Contributors
5.1.4 References

BIBLIOGRAPHY

5.1.1 Introduction

This publication updates and combines information from the Good Practice Guides 89 and 198 already available through the Best Practice Programme.

Extensive use has been made of contributions from equipment manufacturers and other commercial organisations. Contributing organisations are listed in Section 5.1.3 and contact details are given in Module 5.3.

5.1.2 Energy Efficiency Best Practice Programme Publications

The following Energy Efficiency Best Practice Programme publications were extensively used in the preparation of this package:

Good Practice Guide 89	Guide to Compact Heat Exchangers
Good Practice Guide 198	Experience in the Operation of Compact Heat Exchangers
Good Practice Guide 141	Waste Heat Recovery in the Process Industries

5.1.3 External Contributors

The following organisations and individuals contributed technical information, advice, photographs and graphics for the package.

University of Surrey	Professor H. Müller-Steinhagen
Alfa Laval Thermal Division	Mr I. Forrester
APV Heat Exchangers Ltd	Dr M. Ahmed
Engineering Sciences Data Unit (ESDU)	Mr S. Pugh
Heatric Ltd	Ms C. Stacey
Chart Marston Ltd	Mr. P. Shields
HTFS	Dr L. Haseler
OCCO Cooling	Mr B. Withington
Rolls Laval Heat Exchangers Ltd	Mr K. Newman
Fosplant	Mr C. Chapman
Polymer Heat Exchangers	Mr G. Dewson
Packinox / Framatome	Ms R. Elsholz

5.1.4 References

The following specific references were used in Module 3.2 'Fouling'.

1. Marriott, J.: Where and How to Use Plate Heat Exchangers. Chem. Eng., vol. 78, no. 8, pp. 127-134 (1971).

2. Cooper, A., Suitor, J. W., and Usher, J. D.: Cooling Water Fouling in Plate Heat Exchangers. Heat Transfer Eng., Vol. 1, No. 3, pp. 50-55, (1980).

3. Novak, L.: Comparison of the Rhine River and the Öresund Sea Water Fouling and its Removal by Chlorination. Journal of Heat Transfer (1982), Vol. 104, pp. 663-670.

4. Bansal, B. and Müller-Steinhagen, H.M.: Crystallisation Fouling in Plate Heat Exchangers. ASME Journal of Heat Transfer, Vol. 115, pp. 584-591 (1992).

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7. Kho, T.: Effect of Flow Distribution on Scale Formation in Plate and Frame Heat Exchangers. Ph.D. thesis University of Surrey (1998).

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9. Müller-Steinhagen, H. and Zhao, Q. Influence of Low Fouling Surface Alloys Made by Ion Implantation Technology. Chem. Eng. Science, Vol 52, No 19, pp. 3321-3332 (1997).

10. Bornhorst, A., Zhao Q., and Müller-Steinhagen, H.. Reduction of Scale Formation by Ion Implantation and Magnetron Spluttering on Heat Transfer Surfaces. Heat Transfer Engineering, Vol 20, No 2, pp. 6–14 (1999).

11. Masri, M.A. and Cliffe, K.R.: Investigation into the Fouling of a Plate and Frame Heat Exchanger. In Fouling Mitigation of Industrial Heat Exchange Equipment, edts. Panchal, Bott, Somerscales and Toyama. Begel Hse. Inc., pp. 549-561 (1997).

12. Pritchard, A.M., Clarke, R.H. and de Block, M.X.: Fouling of Small Passages in Compact Heat Exchangers. In Fouling Mechanisms: Theoretical and Practical Aspects. edts. Bott et al., Eurotherm Seminar 23, pp. 47-56 (1992).

13. Kew, P.: An Investigation into Fouling of a Printed Circuit Heat Exchanger. Future Practice Report 13, Energy Efficiency Enquiries Bureau, Harwell, UK (1991)

The following specific references were used in Module 3.3 'Applications'.

1. Branch, C.A., Müller-Steinhagen, H., and Seyfried, F.: Heat Transfer to Kraft Black Liquor in Plate Heat Exchangers. APPITA J., Vol 44, No 4, pp. 270-272 (1991).

The following specific references were used in Module 3.5 'Heat Transfer Enhancement'.

1. Reay, D.: Heat Transfer Enhancement – A Review of Techniques and Their Possible Impact on Energy Efficiency in the UK. Heat Recovery Systems and CHP, 11, No 1, pp 1-40 (1991).

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MODULE 5.2

FURTHER INFORMATION

This module provides a list of contacts and independent sources for those interested in obtaining further detailed information on compact heat exchanger technology.

Contents

5.2.1 Introduction
5.2.2 Government Information Contacts
5.2.3 Energy Efficiency Best Practice Programme Publications
5.2.4 Independent Institutions

FURTHER INFORMATION

5.2.1 Introduction

Various sources of information/assistance are available in addition to textbooks and other educational information.

These include:

- Independent organisations, such as Government Departments, the European Commission, and the Energy Efficiency Best Practice Programme.
- Organisations with commercial interests, such as heat exchanger manufacturers, equipment suppliers, consultants and software houses.
- Organisations with vested interests, such as trade associations, study groups, clubs and action groups.

In addition, general information can be found from sources on the Internet.

5.2.2 Government Contacts

The Government co-ordinates energy efficiency initiatives in the UK.

A range of information is available from the Government. This includes:

- Literature from the Energy Efficiency Best Practice Programme, an initiative that incorporates a strategy encouraging the use of compact heat exchangers.
- Information on new types of compact heat exchanger and on related developments.
- Case Studies of successful installations.

The Government has access to sector and technology specialists with a wide experience of industry and technology transfer.

Contact: The Environment and Energy Helpline
Telephone: 0800 585794
Fax: 01235 433066
Email: etbppenvhelp@aeat.co.uk
Website: www.energy-efficiency.gov.uk

ETSU co-ordinates the EEBPP's participation in the International Energy Agency's CADDET Energy Efficiency programme. CADDET provides the latest information on over 1,700 international case studies featuring technologies demonstrated in industrial, transport and buildings sectors. Information is easy to access through the Internet and publications, including Technical Brochures and a quarterly Newsletter, are available from the Environment and Energy Helpline. Twelve countries from around the world contribute data to CADDET. To learn from this vast range of international experience, 27 Analysis Reports have been published that critically evaluate the factors leading to successful implementation of technologies. These also can be purchased for £17.50 through the Helpline.

Contact: The Environment and Energy Helpline
Telephone: 0800 585794
Fax: 01235 433066
Email: etbppenvhelp@aeat.co.uk
Website: www.caddet-ee.org

The European Commission

The European Commission can put you in contact with:

- The ENERGIE programme for research, technology development and demonstration.

Contact: Mrs Sarah Talbot
Energie Helpline UK
Telegraphic House
Waterfront Quay
Salford Quays
Manchester M5 2XW
Telephone: 0161 874 3636
Fax: 0161 874 3644
Email: energie@march-consulting.co.uk
Website: www.dti.gov.uk/ent/energie

5.2.3 Energy Efficiency Best Practice Programme Publications

The following publications concerning compact heat exchangers and related topics are available from:

The Environment and Energy Helpline
Telephone: 0800 585794
Fax: 01235 433066
Email: etbppenvhelp@aeat.co.uk
Website: www.energy-efficiency.gov.uk

Good Practice Guides

Good Practice Guide 89	Guide to Compact Heat Exchangers
Good Practice Guide 198	Experience in the Operation of Compact Heat Exchangers
Good Practice Guide 141	Waste Heat Recovery in the Process Industries
Good Practice Guide 168	Cutting Your Energy Costs
Good Practice Guide 244	Process Integration

Future Practice

Future Practice R&D Profile 46	A Compact Titanium Heat Exchanger Made by Superplastic Forming and Diffusion Bonding.
Future Practice Report 13	An Investigation into Fouling of a Printed Circuit Heat Exchanger.
Future Practice Report 28	A Market and Project Study of Gas Turbine Small-scale Combined Heat and Power.
Future Practice R&D Profile 12	Testing of Printed Circuit Heat Exchangers.
Future Practice R&D Profile 30	Improved Process Design using Multi-stream Heat Exchangers.
Future Practice R&D Profile 61	The Development of a Diffusion Bonded Stainless Steel Fin Heat Exchanger.
New Practice Final Profile 65	White Water Heating with Fluidised Bed Heat Exchangers.
Future Practice R&D Profile 82	Design Technology for Compact Integrated Reactor Heat Exchangers.

5.2.4 Independent Institutions

There are independent cross-technology organisations promoting the technical aspects of heat exchanger technology in the UK. These organisations may also have commercial interests.

Advanced Heat Exchanger Action Group (HEXAG)
A technical forum for information interchange on all aspects of heat exchange advances.

Contact: Professor David Reay
PO Box 25, Whitley Bay, Tyne and Wear NE26 1QT.
Telephone: 0191 251 2985
Fax: 0191 252 2229
E-mail: DAReay@aol.com
Internet: www.hw.ac.uk/mecWWW/hexag/WebPage

Heat Transfer Society
An industrial forum for interchange of heat transfer information with a regular newsletter.

Contact: Mr G. Bowes
26 Celandine Bank, Woodmancote, Cheltenham, Gloucester GL52 4HZ.

Compact Heat Exchanger Study Group
A subscription-based club providing technical information exchange and specifications to club members.

Contact: Mr Lawrence Daniels
AEA Technology, Harwell, Didcot, Oxfordshire OX11 0RA.
Telephone: 01235 432060

Heat Transfer and Fluid Flow Service (HTFS)
HTFS provides heat exchanger and process integration software. Website includes some lecture material on compact heat exchangers.

Contact: Mr R Brogan
HTFS, 392.7, Harwell, Didcot, Oxfordshire OX11 0RA.
Telephone: 01235 432819
Fax: 01235 831981
Internet: www.aeat.co.uk/pes/htfs/index.html

Engineering Sciences Data Unit (ESDU)

ESDU publishes engineering data on heat exchangers including compact heat exchangers. Further information on the full range of process engineering and heat transfer design methods for compact heat exchangers are available. All ESDU data is available to subscribing universities and companies from the ESDU Website.

Contact: Simon Pugh
ESDU International plc.
27 Corsham Street, London N1 6UA.
Telephone: 020 7490 5151
Fax: 020 7490 2701
E-mail: sjpugh@esdu.com
Internet: www.esdu.com

Heat Transfer Research Inc. (HTRI)

Heat Transfer Research, Inc. conducts research on industrial-scale heat transfer equipment, develops software modelling and simulation tools based on proprietary research data, and provides other technical services and training.

Contact: Fernando Aguirre
Heat Transfer Research, Inc.
The Surrey Technology Centre, 40 Occam Road, The Surrey Research Park, Guildford, Surrey GU2 5YG
Telephone 01483 851623
Fax: 01483 851624
E-mail: fja@htri.net

Brazed Aluminium Plate-Fin Exchangers Manufacturers Association (ALPEMA)

ALPEMA was formed to promote the broader use of brazed aluminium plate-fin heat exchangers in existing and new markets.

Contact: David Butterworth
ALPEMA General Secretary
29 Clevelands, Abingdon, Oxfordshire, OX14 2EQ.
Telephone: 01235 525955
Fax: 01235 200906
E-mail: DaveButterworth@compuserve.com
Internet: www.aeat.co.uk/alpema/index.html

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 5.3

TECHNOLOGY SUPPLIERS

This module provides a list of suppliers of compact heat exchangers, which is intended to assist potential users in finding suitable equipment and in obtaining more detailed information and quotations.

Contents

5.3.1 Plate and Frame Heat Exchangers
5.3.2 Plate Heat Exchangers (Brazed)
5.3.3 Plate Heat Exchangers (Welded)
5.3.4 Plate-Fin Heat Exchangers
5.3.5 Printed Circuit Heat Exchangers
5.3.6 Plate and Shell Heat Exchangers
5.3.7 Compact Shell and Tube Heat Exchangers
5.3.8 Spiral Heat Exchangers
5.3.9 HEX Reactors

The technology supplier list provided is not exhaustive and has been compiled from information currently available. The listing of a supplier does not constitute an endorsement and neither does the omission of a supplier discriminate against its competence.

The names and addresses of other suppliers may be found in commercially available directories or obtained from trade associations.

TECHNOLOGY SUPPLIERS

5.3.1 Plate and Frame Heat Exchangers

Alfa Laval Ltd, Thermal Division.
Doman Road, Camberley, Surrey. GU15 3DN
Tel: 01276 63383
Fax: 01276 413601

APV EAME
PO Box 4, Gatwick Road, Crawley, W Sussex. RH10 2QB
Tel: 01293 527777
Fax: 01293 552640

Barriquand Echangeurs
Export Office, 144 rue Celestin Demblon, 4630 Soumagne, Belgium
Tel: +32 437 742 49
Fax: +32 437 749 74

UK Importers:
Fosplant
Weir Bank, Bray-on-Thames, Maidenhead, Berks. SL6 2ED
Tel: 01628 762740
Fax: 01628 762741

Brautek Ltd
PO Box 222, Bury St Edmunds, Suffolk. IP28 6EE
Tel: 01284 728150
Fax: 01284 728155

GEA Aktiengesellschaft
PO Box 100830, 44708 Bochum. Germany
Tel: +49 234 980 0
Fax: +49 234 980 1087

UK Importers:
OCCO Coolers
Factory and Sales (North), Dawley Bank, Telford, Shropshire. TF4 2BS.
Tel: 01952 630361
Fax: 01952 502785

OCCO Coolers
Sales Office (South), 7 Town Hall, Beaconsfield, Bucks. HP9 2PP
Tel: 01494 673458
Fax: 01494 677060

HRS Process Engineering Ltd.
HRS House, 10-12 Caxton Way, Watford Business Park, Watford, Herts, WD1 8TX
Tel: 01923 232335
Fax: 01923 230266

SWEP Ltd.
Chobham Ridges, The Maultway, Camberley, Surrey. GU15 1QE
Tel: 01276 64221
Fax: 01276 64344

Wincanton Engineering Ltd
South Street, Sherbourne, Dorset, DT9 3ND
Tel: 01935 813741
Fax: 01935 814548

5.3.2 Plate Heat Exchangers (Brazed)

Alfa Laval Ltd, Thermal Division.
Doman Road, Camberley, Surrey. GU15 3DN
Tel: 01276 63383
Fax: 01276 413601

EJ Bowman (Birmingham) Ltd
Chester Street, Birmingham, West Midlands. B6 4AP
Tel: 0121 359 5401
Fax: 0121 359 7495

GEA Aktiengesellschaft
PO Box 100830, 44708 Bochum. Germany
Tel: +49 234 980 0
Fax: +49 234 980 1087

UK Importers:

OCCO Coolers
Factory and Sales (North), Dawley Bank, Telford, Shropshire. TF4 2BS.
Tel: 01952 630361
Fax: 01952 502785

OCCO Coolers
Sales Office (South), 7 Town Hall, Beaconsfield, Bucks. HP9 2PP
Tel: 01494 673458
Fax: 01494 677060

HRS Process Engineering Ltd.
HRS House, 10-12 Caxton Way, Watford Business Park, Watford, Herts, WD1 8TX
Tel: 01923 232335
Fax: 01923 230266

5.3.3 Plate Heat Exchangers (Welded)

Alfa Laval Ltd, Thermal Division.
Doman Road, Camberley, Surrey. GU15 3DN
Tel: 01276 63383
Fax: 01276 413601

Barriquand Echangeurs
Export Office, 144 rue Celestin Demblon, 4630 Soumagne, Belgium
Tel: +32 437 742 49
Fax: +32 437 749 74

UK Importers:
Fosplant
Weir Bank, Bray-on-Thames, Maidenhead, Berks. SL6 2ED
Tel: 01628 762740
Fax: 01628 762741

OCCO Coolers
Sales Office (South), 7 Town Hall, Beaconsfield, Bucks. HP9 2PP
Tel: 01494 673458
Fax: 01494 677060

Packinox S.A.
Tour Framatome, 92084 Paris la Defense, France
Tel: +33 147 963 434
Fax: +33 147 963 440

Hunt Thermal Engineering
Astley St, Dukinfield, Cheshire SK16 4QT
Tel: 0161 331 4400
Fax: 0161 330 9417

5.3.4 Plate-Fin Heat Exchangers

Chart Marston Ltd.
Wobaston Road, Fordhouses, Wolverhampton, WVlO 6QJ
Tel: 01902 397777
Fax: 01902 397792

Normalair-Garrett Ltd.
Garrett Road, Lynx Trading Estate, Yeovil, Somerset, BA20 2TH
Tel: 01935 475181
Fax: 01935 427600

Rolls Laval Heat Exchangers Ltd.
PO Box 100, Ettingshall, Wolverhampton, West Midlands. WV4 6JY.
Tel: 01902 353353
Tel: 01902 403334

Nordon Cryogenie
25 Rue du Fort, BP 87, 88194 Golbey Cedex, France
Tel: +33 329 680000
Fax: +33 329 313621

5.3.5 Printed Circuit Heat Exchangers

Heatric Ltd.
46 Holton Road, Holton Heath, Poole, Dorset. BH16 6LT
Tel: 01202 627000
Fax: 01202 632299

5.3.6 Plate and Shell Heat Exchangers

APV EAME
PO Box 4, Gatwick Road, Crawley, W Sussex. RH10 2QB
Tel: 01293 527777
Fax: 01293 552640

OCCO Coolers
Factory and Sales (North), Dawley Bank, Telford, Shropshire. TF4 2BS.
Tel: 01952 630361
Fax: 01952 502785
Sales Office (South), 7 Town Hall, Beaconsfield, Bucks. HP9 2PP
Tel: 01494 673458
Fax: 01494 677060

5.3.7 Compact Shell and Tube Heat Exchangers

EJ Bowman (Birmingham) Ltd
Chester Street, Birmingham, West Midlands. B6 4AP
Tel: 0121 359 5401
Fax: 0121 359 7495

Britannia Heat Transfer
Unit 15, Coleshill Industrial Estate, Coleshill, Birmingham. B46 1JT
Tel: 01675 466060
Fax: 01675 467675

Brown Fintube UK Ltd
PO Box 790, Wimbourne, Dorset. BH21 5YA
Tel: 01258 840776
Fax: 01258 840961

Ametek Inc.

UK Agents Polymer Exchangers
Hollins Lane, Tilstock, Whitchurch, Shropshire. SY13 3NU
Tel: 01948 880627
Fax: 01948 880339

Serek Heat Transfer
Warwick Road, Birmingham, West Midlands. B11 2QY
Tel: 0121 766 6666
Fax: 0121 766 6014

5.3.8 Spiral Heat Exchangers

Alfa Laval Ltd, Thermal Division.
Doman Road, Camberley, Surrey. GU15 3DN
Tel: 01276 63383
Fax: 01276 413601

GEA Aktiengesellschaft
PO Box 100830, 44708 Bochum. Germany
Tel: +49 234 980 0
Fax: +49 234 980 1087

UK Importers:

OCCO Coolers
Factory and Sales (North), Dawley Bank, Telford, Shropshire. TF4 2BS.
Tel: 01952 630361
Fax: 01952 502785

OCCO Coolers
Sales Office (South), 7 Town Hall, Beaconsfield, Bucks. HP9 2PP
Tel: 01494 673458
Fax: 01494 677060

5.3.9 HEX Reactors

Chart Marston Ltd.
Wobaston Road, Fordhouses, Wolverhampton, WVlO 6QJ
Tel: 01902 397777
Fax: 01902 397792

GUIDE TO COMPACT HEAT EXCHANGERS

MODULE 5.4

ENERGY EFFICIENCY BEST PRACTICE PROGRAMME

This module provides general information on the Energy Efficiency Best Practice Programme, a Government funded initiative.

Contents

5.4.1 Introduction
5.4.2 The Energy Efficiency Best Practice Programme
5.4.3 How to Contact the Programme

ENERGY EFFICIENCY BEST PRACTICE PROGRAMME

5.4.1 Introduction

In the UK we use over £50 billion worth of energy each year. However we waste 20% of it and, apart from the money we could all save by using energy more efficiently, we could also reduce emissions into the atmosphere that increase local pollution levels and contribute to climate change.

The Energy Efficiency Best Practice Programme (EEBPP) is a UK Government programme designed to help organisations cut their energy bills by 10-20%. It provides independent advice and assistance to UK private and public sector organisations. Since it was established in 1989, the EEBPP has helped many UK organisations to reduce their energy bills and to improve profitability and investment returns. It has stimulated UK energy savings of around £650 a year.

The Energy Efficiency Best Practice Programme is a Government funded initiative. The buildings and services part of the Energy Efficiency Best Practice Programme is managed by BRECSU. The part of the Programme relating to industrial processes and utilities is managed by the Energy Technology Support Unit (ETSU), part of AEA Technology Plc.

In 1999 the Government spent £16 million on its Energy Efficiency Best Practice Programme. This figure is scheduled to rise to £20 million per annum over the next couple of years. This is a significant investment for the taxpayer, but one that is paying off handsomely for the thousands of organisations and professions who have used the programme.

5.4.2 The Energy Efficiency Best Practice Programme

The Energy Efficiency Best Practice Programme supports R&D into new energy efficiency measures; gathers impartial information on the effectiveness of carefully identified measures; and disseminates it to target audiences.

Help and advice are provided through:

- A national energy and environmental helpline.
- Free publications.
- Seminars, workshops and conference events.
- Site energy surveys and site specific advice.
- Building design advice consultancies.
- Electronic media including a Website, software and CD-ROM material.
- Sectorial benchmarking schemes.
- Energy efficiency agreements to achieve specific targets.

So far, the Programme has helped the UK economy save £650 million annually (equivalent to 3 million tonnes carbon emission saving per year) since it started in 1989. At a cost to the taxpayer of a few tens of pounds per tonne, it is the Government's most cost-effective energy efficiency programme. It is on track to achieve its target of stimulating annual energy savings worth £800 million (5 million tonnes of carbon emission saving per year) by the end of 2000.

Best Practice is successful because:

- The approach appeals to senior management as structured, effective and complementary to good management practice.
- Information provided is practical, impartial, authoritative and free at the point of use.
- It provides a route whereby appropriate R&D projects are supported and then encouraged to market.
- Everyone involved benefits through reduced costs, better working and living conditions, reduced environmental impact and a more sustainable future.

Thousands of organisations have used Energy Efficiency Best Practice to save energy and reduce carbon dioxide emission. Companies large and small, hospitals, schools, local authorities, commerce, process and manufacturing industry, building professionals, housing stock managers and many more have used Best Practice information to improve their energy efficiency performance.

Further information on Energy Efficiency Best Practice Programme publications is given in section 5.2.3.

5.4.3 How to Contact the Programme

For further information about Energy Efficiency Best Practice Programme, contact the Environment and Energy Helpline on 0800 585794.

Alternatively, visit the Programme Website at www.energy-efficiency.gov.uk